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Evaluation of Composite Structures Technologies for Application to NASA's Vision for Space Exploration (CoSTS)

Ravi Deo, Donny Wang, Jim Bohlen, and Cliff Fukuda
Northrop Grumman Corporation, Integrated Systems Sector, El Segundo, California

July 2008

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Table of Contents

FOREWORD

This report documents work completed on Evaluation of Composite Structures Technologies for Application to NASA's Vision for Space Exploration (abbreviated CoSTS), a Task Order under NASA Contract NNL04AA13B. The work was performed by Northrop Grumman's Integrated Systems Sector, Western Region, El Segundo, California. Dawn Jegley, NASA Langley Research Center, was the NASA Contracting Officer's Technical Representative. Ravi Deo was Program Manager for the Northrop Grumman Corporation. Cliff Fukuda researched the configurations of the baseline Space Exploration vehicles, and established "need" dates for the technologies; Donny Wang set up the initial spreadsheets and prepared interim and final presentations; Jim Bohlen obtained technology ranking data from subject matter experts, developed a consensus ranking system and developed all the spreadsheets used in making the final recommendations; Jim Berry provided the "gear ratio" data quantifying the system mass savings as a function of an exploration vehicle element mass savings, which were then used to weight the consensus rankings obtained. Jim Bohlen and Donny Wang performed the final evaluation of technologies and recommended rankings.

SUMMARY

A trade study was conducted to determine the suitability of composite structures for weight and life cycle cost savings in primary and secondary structural systems for crew exploration vehicles, crew and cargo launch vehicles, landers, rovers, and habitats. The results of the trade study were used to identify and rank order composite material technologies that can have a near-term impact on a broad range of exploration mission applications.

Based on the result, a set of composite technology developments along with preliminary roadmaps were developed as recommendations for future work. In general, when weighted for their mass savings payoffs, i.e., higher in the stack the more beneficial, technologies applicable to composite usage in lunar lander and lunar surface elements dominated the list of promising technologies. Recognizing, however, that significant weight savings can also be achieved in heavy lift vehicle such as Ares V, composite technology needs for this class of launch vehicles were also identified. This report recommends technologies that should be developed to enable usage of composites on Vision for Space Exploration vehicles towards mass and life-cycle cost savings.

INTRODUCTION

Vision for Space Exploration's (VSE's) initial goal is to return humans to the Moon by the year 2020. The Moon will serve as a testing ground for eventual sustained human and robotic exploration of Mars and other destinations. Central to the VSE is the development of new space vehicles for cargo and crew transportation. These vehicles currently contained in NASA's Constellation Program (CxP) include Ares I Crew Launch Vehicle, the Ares-V Heavy Lift Cargo Launch Vehicle, the Orion Crew Exploration Vehicle, and the Lunar Lander. These vehicles and their structural components are expected to be mass critical, and will therefore, benefit from novel and lightweight advanced composite structural concepts. In addition to the transportation vehicles, a variety of lunar surface infrastructure elements such as habitats, rovers, payload handling devices, equipment for in-situ resource utilization (ISRU), storage structures, and scientific instruments and platforms will be required. Advanced composite structures usage in these lunar surface elements promises significant benefits towards offsetting the premium inherent in landing mass at the lunar surface.

The specific objectives of the proposed task were to first, survey and study composite structures technologies and identify those with potential for reducing CxP architecture element weight and costs at an acceptable risk. The next objective was to evaluate and rank these technologies by their relative importance in impacting CxP missions in terms of potential weight reduction, DDT&E cost savings over baseline, and life cycle cost savings at a reliability equivalent to or greater than the baseline. The final objective was to assess the degree of difficulty inherent in maturing the technologies over the time period leading to the PDR of the respective CxP architecture elements. The architecture elements considered in this task and their respective PDR dates are summarized in the schedule shown in Figure 1 (Ref. 1).

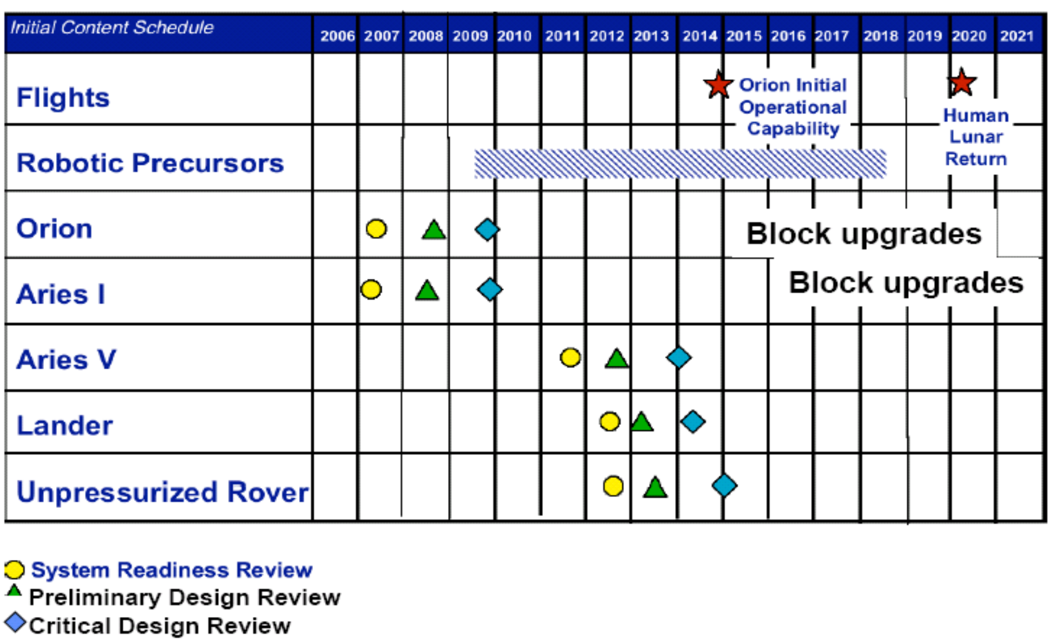


Figure 1. Composites Technology Requirement Dates for Space Exploration Vehicles.

Identifying candidate vehicle components and applicable composite materials, structures and manufacturing technologies was the first step in the approach to accomplishing the objectives of this task. Subject Matter Experts (SME) then evaluated the importance of the technologies with respect to the vehicle components. Allowance was also made to recognize quantitatively that the higher up in the launch stack that a component belonged, the greater was the overall systems weight savings. This characteristic was captured by means of so-called “gear ratios” calculated using the rocket equation and the destination of the mass. The SME provided data were used to perform trade studies using a Quality Function Deployment (QFD) type methodology to rank order the technologies for a variety of criteria.

The process used to perform the trade study and the results are presented in this contractor’s Report. Recommendations for future technology development activities were derived from the trade studies and are also presented in the balance of this report.

TECHNOLOGY RANKING METHODOLOGY

In general, the technology ranking methodology began with identifying the candidate structural components and the potential composite materials, structures and manufacturing technologies required. The technologies were then ranked by their relevance and relative importance in reducing mass and cost. Significant aspects of the methodology including use of consensus in numerically rating the technologies and using weighting factors that allocate a premium to a technology based on the mass saved in the upper stages are described in this section.

Candidate Structures

The CxP elements or vehicles considered for composites application were:

- Ares I Launch Vehicle and the Orion Module considered as a system
- Ares V Launch Vehicle including the Earth Departure Stage (EDS)
- Lunar Lander
- Lunar Habitat
- Lunar Mobility Chassis

Each of these elements/vehicles was further decomposed into structural sub-components such as interstages, cryotanks, adapters, and landing legs. The total number of sub-components selected to sufficiently capture the weight savings potential of composites was 44.

The baseline element/vehicle configurations were provided by NASA (Refs. 2, 3, and 4) and are shown in Appendix A. The 44 subcomponents are listed in the spreadsheets for each technology category shown in Appendix B. These spreadsheets were the root data collection tool for the trade studies conducted in this task.

Composite Materials, Structures and Manufacturing Technologies

Seven broad categories of composites technologies were compiled from NASA internal and Industry provided needs for advanced composite space structures. These technology categories were:

- Materials and Processes
- Manufacturing Methods
- Innovative Design
- Advanced Analysis and Simulation
- Design Criteria and Allowables
- Development, Quality Assurance and Certification
- Threat and Environment

Within these seven broad categories, multiple specific advances and developments were identified as being necessary to enable or enhance composite space vehicle structures. These technologies and the specific developments required are shown as column headings in the spreadsheets of Appendix B.

Technology Ranking Process

The process used is schematically illustrated in Figure 2 and began with developing the spreadsheets given in APPENDIX B consisting of the 44 structural components and 84 technology sub-categories. The spreadsheets were then provided to the subject matter

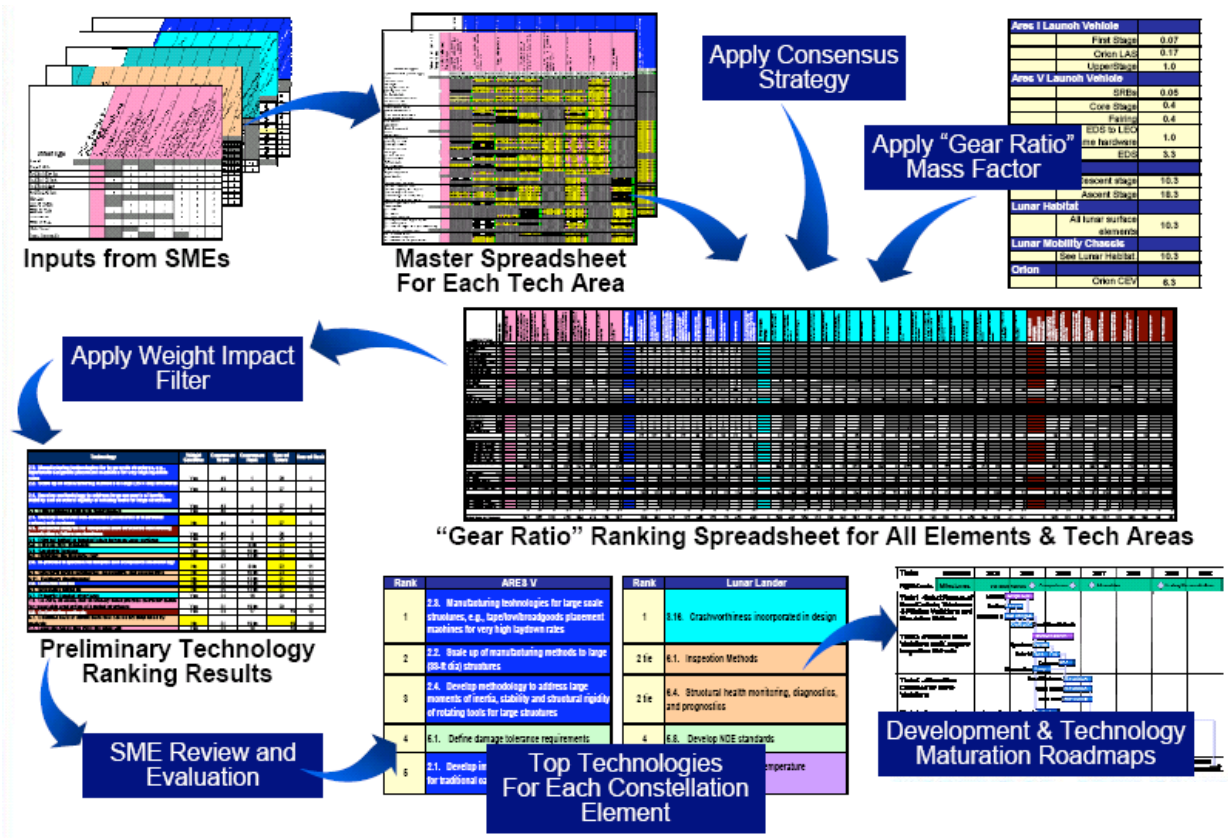


Figure 2. Schematic Illustration of the Technology Ranking and Selection Process

1**Figure 2. Schematic Illustration of the Technology Ranking and Selection Process**

experts for numerical scoring. To facilitate the SMEs the spreadsheet input required was reduced from having to fill in 3696 cells (44X84), to perhaps 40 percent of that number by inspecting the spreadsheets and "graying" out cells where there was no relevance or where the technology sub-category considered did not apply. The SMEs were given the authority, however, to change the "gray" status of a cell if they had justification to do so.

The subject matter experts selected for scoring were specialists with substantial knowledge and experience in materials and processes, composites manufacturing, structural design and analysis, durability and damage tolerance of structures, spacecraft design, systems engineering, quality assurance and certification of human rated structures. Northrop Grumman qualifications and experience that the SMEs relied on is summarized in APPENDIX D.

For consistency**,** the SMEs were instructed to score the master spreadsheets as follows:

a. the scores can only be 0,1, 3 or 5
b. 0 represents no applicability
c. 1 represents technology that can provide some improvement
d. 3 represents technology that is enhancing, e.g., improvement in TPM between 10%-20%
e. 5 represents technology that is significantly enhancing or enabling with TPM>20%
f. Note any special assumptions by inserting comments in appropriate cells

As shown in Figure 2, the SME scores were assembled on seven Master Spreadsheets, one for each technology area, to establish consensus numbers for each cell. The strategy used to determine a consensus number was to obtain a majority score and re-visit the SMEs with scores that deviated by more than 1 point to understand their perspective. If the difference could not be negotiated and remained large enough to be an outlier, the majority or dominant score was used. At the completion of this process, the spreadsheet sample shown in Figure 3 was derived. In this

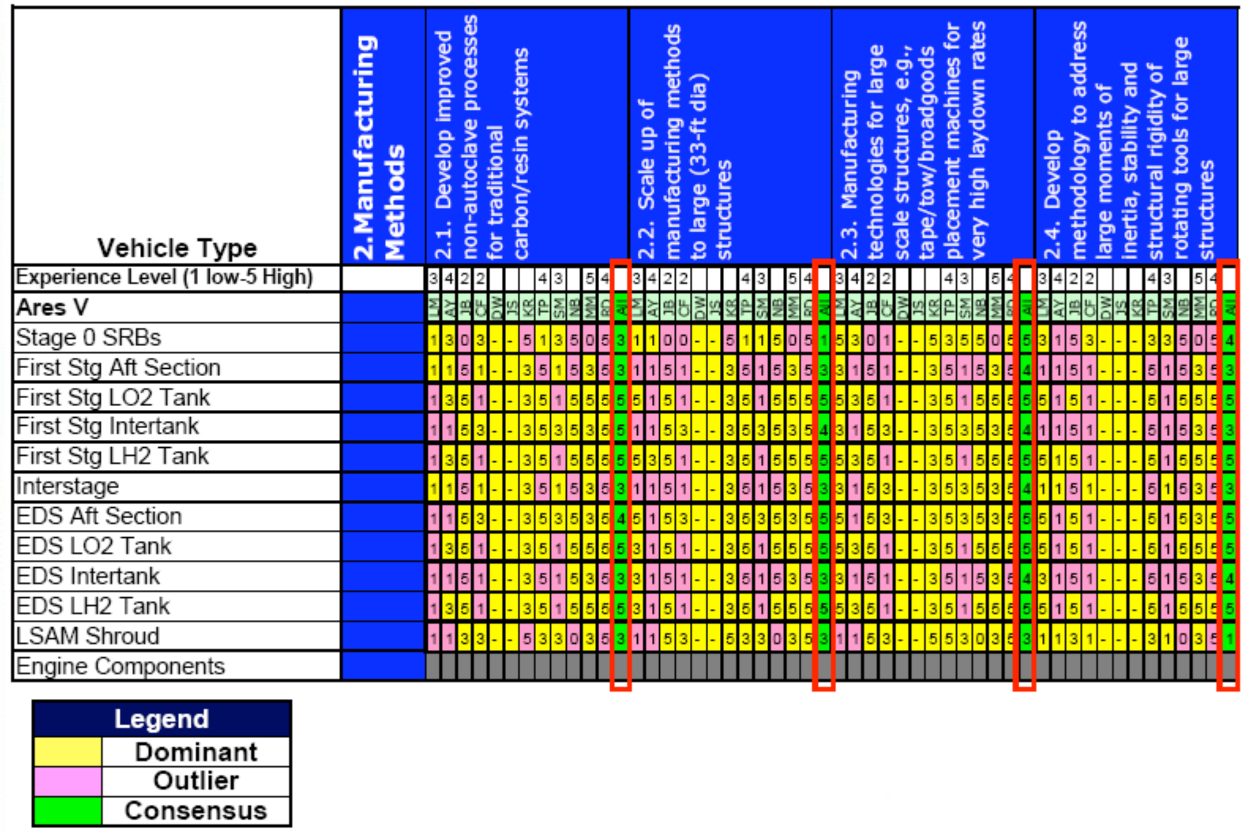


Figure 3. Schematic Illustration of the Technology Ranking and Selection Process

figure, which shows some of the manufacturing method ratings. The dominant score is color coded yellow and the consensus number is shown in red boxes with green colored cells. As can be seen in the figure, outliers are not a rare occurrence. However, the yellow cells dominate giving some confidence in the consensus numbers. Based on this strategy for establishing consensus scores, a Consensus Master Spreadsheet was developed as illustrated by a small section of it shown in Figure 4. As can be seen from the subtotal scores in the figure, manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates is the most important technology sub-category within manufacturing methods for the Ares V launch vehicle. For a relative ranking of technologies across all elements considered, however, the system level impact of mass savings realized for

Vehicle Type	2. Manufacturing Methods	2.1. Develop improved non-autoclave processes for traditional carbon/resin systems	2.2. Scale up of manufacturing methods to large (33-ft dia) structures	2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates	2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures	2.5. Vented core and core splicing technology development	2.6. In-process inspection techniques and acceptance methodology	2.7. Nontraditional cure methods such as ultrasonics	2.8. Low-cost tooling	2.9. Improved assembly process such as self-tooling, reducing imperfections and guaranteeing adequate tolerance
Ares V										
Stage 0 SRBs		3	1	5	4	1	3	2	3	3
First Stg Aft Section		3	3	4	3	1	3	3	3	1
First Stg LO2 Tank		5	5	5	5	5	4	3	3	3
First Stg Intertank		5	4	4	3	1	3	1	3	3
First Stg LH2 Tank		5	5	5	5	5	4	3	3	3
Interstage		3	3	4	3	1	3	3	3	1
EDS Aft Section		4	5	5	5	1	3	3	3	2
EDS LO2 Tank		5	5	5	5	5	4	3	3	3
EDS Intertank		3	3	4	4	1	3	3	3	3
EDS LH2 Tank		5	5	5	5	5	4	3	3	3
LSAM Shroud		3	3	3	1	1	3	1	4	2
Engine Components									1	
Subtotal		**44**	**42**	**49**	**43**	**27**	**37**	**28**	**35**	**27**

Figure 4. Sample of Consensus Master Spreadsheet. Subtotals Indicate Scores for a CxP Element.

each of these elements was calculated to determine the leverage or "gear ratio" offered and then used as a multiplier to emphasize high payoff technologies. This leverage or "gear ratio" was termed the mass multiplier and was calculated from the rocket equation as the system mass reduction per unit of component mass reduction assuming the component is launched to Low Earth Orbit (LEO) for a lunar mission. The calculated weight multipliers for each element considered in this task are summarized in Figure 5.

Ares I/Orion	
First Stage	0.07
Orion LAS	0.17
Upper Stage	1.0
Orion CEV	6.3
Ares V	
SRBs	0.05
Core Stage	0.4
Fairing	0.4
EDS to LEO	1.0
EDS	3.3
Lunar Lander	
Descent Stage	10.3
Ascent Stage	18.3
Lunar Habitat	
All Lunar Surface Elements	10.3
Lunar Mobility Chassis	
See Lunar Habitat	10.3

- System Mass Reduction Per Unit Of Component Mass Reduction. Relative Value Of Element Dry Mass Vs. One Unit Of Mass Launched To LEO In Support Of A Lunar Mission
- Approximate IMLEO (Initial Mass In LEO) "Gear Ratio"
- All Lunar Surface Elements Are Assumed To Have Same "Gear Ratio" As The Nominal Descent Stage
- Surface Element Reuse During Multiple Missions Ignored

Significant Weight Savings Payoffs In Upper Stages Influence Technology Priorities

Figure 5. System Mass Reduction per Unit of Component Mass Reduction for the Component Launched to LEO in Support of a Lunar Mission.

The next step performed in the process shown in Figure 2 was to apply the mass multiplier to the consensus ratings and obtain a "gear ratio" weighted score for each element across all technology sub-categories. A sample of the mass multiplier or "gear ratio" weighted score for Ares V is shown in Figure 6. These subtotals when compared with the Consensus subtotals are lower because the value of the multiplier is at most 1.0. In other words, mass savings at the first stage of the launch vehicle has to be significant before it can lead to system level mass savings.

Vehicle Type	Gear Ratio	2. Manufacturing Methods	2.1. Develop improved non-autoclave processes for traditional carbon/resin systems	2.2. Scale up of manufacturing methods to large (33-ft dia) structures	2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates	2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures	2.5. Vented core and core splicing technology development	2.6. In-process inspection techniques and acceptance methodology	2.7. Nontraditional cure methods such as ultrasonics	2.8. Low-cost tooling	2.9. Improved assembly process such as self-tooling, reducing imperfections and guaranteeing adequate tolerance
Ares V											
Stage 0 SRBs	0.05		0.15	0.05	0.25	0.2	0.05	0.15	0.1	0.15	0.15
First Stg Aft Section	0.40		1.2	1.2	1.6	1.2	0.4	1.2	1.2	1.2	0.4
First Stg LO2 Tank	0.40		2	2	2	2	2	1.6	1.2	1.2	1.2
First Stg Intertank	0.40		2	1.6	1.6	1.2	0.4	1.2	0.4	1.2	1.2
First Stg LH2 Tank	0.40		2	2	2	2	2	1.6	1.2	1.2	1.2
Interstage	0.40		1.2	1.2	1.6	1.2	0.4	1.2	1.2	1.2	0.4
EDS Aft Section	1.00		4	5	5	5	1	3	3	3	2
EDS LO2 Tank	1.00		5	5	5	5	5	4	3	3	3
EDS Intertank	1.00		3	3	4	4	1	3	3	3	3
EDS LH2 Tank	1.00		5	5	5	5	5	4	3	3	3
LSAM Shroud	0.40		1.2	1.2	1.2	0.4	0.4	1.2	0.4	1.6	0.8
Engine Components	1.00									4	
Subtotal			27	27	29	27	18	22	18	21	16
Consensus Subtotal			44	42	49	43	27	37	28	35	27

Figure 6. Mass Multiplier or "Gear Ratio" Weighted Score for Ares V. For Comparison Subtotal from the Consensus Score Also Shown.

It should be noted from Figure 6 that within an element or a vehicle the relative values of the sub-totals remain the same as in the consensus subtotal thus retaining the same technology priorities for a given element.

The consensus and mass multiplier weighted scores are compared for all elements for Manufacturing Methods Technology sub-categories in Figure 7. A comparison shows an order of magnitude change in the "gear ratio" weighted scores and that the lunar elements dominate the total scores after the mass multiplier has been applied. As a consequence Improved Assembly Processes development now is the most important technology subcategory as opposed to Manufacturing Technology for large scale structures. These effects of "gear ratio" weighting are accounted for in setting technology priorities based on the results of the process summarized in Figure 2. The remaining steps in Figure 2, namely applying "Weight Impact Filter", Identifying top technologies for each Constellation element, and developing technology maturation roadmaps are significant in terms of the results of the methodology applied here and are discussed in the following section on Technology Priorities for Individual Constellation Elements.

Vehicle Type	2. Manufacturing Methods	2.1. Develop improved non-autoclave processes for traditional carbon/resin systems	2.2. Scale up of manufacturing methods to large (33-ft dia) structures	2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates	2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures	2.5. Vented core and core splicing technology development	2.6. In-process inspection techniques and acceptance methodology	2.7. Nontraditional cure methods such as ultrasonics	2.8. Low-cost tooling	2.9. Improved assembly process such as self-tooling, reducing imperfections and guaranteeing adequate tolerance
Ares I/Orion		20	14	20	15	18	36	12	30	0
Ares V		44	42	49	43	27	37	28	35	27
Lunar Lander		0	0	1	1	23	0	0	14	22
Lunar Habitat		10	11	6	6	2	6	2	12	12
Lunar Mobility		2	2	0	0	0	0	0	5	3
Consensus Total		**76**	**69**	**76**	**65**	**70**	**79**	**42**	**96**	**64**

Vehicle Type	2. Manufacturing Methods	2.1. Develop improved non-autoclave processes for traditional carbon/resin systems	2.2. Scale up of manufacturing methods to large (33-ft dia) structures	2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates	2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures	2.5. Vented core and core splicing technology development	2.6. In-process inspection techniques and acceptance methodology	2.7. Nontraditional cure methods such as ultrasonics	2.8. Low-cost tooling	2.9. Improved assembly process such as self-tooling, reducing imperfections and guaranteeing adequate tolerance
Ares I/Orion		59	31	37	20	36	94	31	66	0
Ares V		27	27	29	27	18	22	18	21	16
Lunar Lander		0	0	18	18	325	0	0	208	323
Lunar Habitat		103	113	62	62	21	62	21	124	124
Lunar Mobility		21	21	0	0	0	0	0	52	31
Geared Total		**209**	**193**	**147**	**127**	**400**	**178**	**70**	**470**	**493**

Ares I/Orion	
First Stage	0.07
Orion LAS	0.17
Upper Stage	1.0
Orion CEV	6.3
Ares V	
SRBs	0.05
Core Stage	0.4
Fairing	0.4
EDS to LEO	1.0
EDS	3.3
Lunar Lander	
Descent Stage	10.3
Ascent Stage	18.3
Lunar Habitat	
All Lunar Surface Elements	10.3
Lunar Mobility Chassis	
See Lunar Habitat	10.3

Lunar Elements Dominate Total Scores After "Gear Ratio" Applied

Figure 7. Mass Multiplier or "Gear Ratio" Weighted Score Totaled for All Elements Compared with Consensus Scores Totaled Across All Elements.

TECHNOLOGY PRIORITIES FOR INDIVIDUAL CONSTELLATION ELEMENTS

Results of applying the technology ranking methodology of Figure 2 in the preceding section are presented and discussed in the following paragraphs. The effect of the mass multiplier or "gear ratio" is examined along with how priorities change when technologies that are material neutral or do not directly impact structural mass, e.g., Low-Cost Tooling, are filtered out. Finally, the top ranked technologies for individual Constellation elements and for the case where Lunar elements are dominant are presented. These data form the basis of the recommendations made in the following section of this report.

Comparison of Consensus and Mass Multiplier Weighted Technology Ranking

Figure 8 shows a comparison of the Consensus Score and the mass multiplier or "gear ratio" adjusted score for the top 10 technologies that emerged for the Ares V launch vehicle only. As seen in the figure, the "gear ratio" adjustment does somewhat influence the technology rank for Ares V. Of the top 5 technologies, 4 are manufacturing and manufacturing scale up related, followed by key safety concerns such as damage tolerance.

Technology	Consensus Score	Consensus Rank	Adjusted Score*	Adjusted Rank*
2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates	49	1	29	1
2.2. Scale up of manufacturing methods to large (33-ft dia) structures	42	5	27	2
2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures	43	4	27	3
5.1. Define damage tolerance requirements	40	7	27	4
2.1. Develop improved non-autoclave processes for traditional carbon/resin systems	44	3	27	5
4.1. Advanced analysis for composite shell structures considering imperfections, failure mechanisms	45	2	26	6
3.1. Efficient bolted or bonded joints between large sections	41	6	25	7
5.8. Develop NDE standards	37	8 tie	23	8
3.3. Sandwich Designs	36	10 tie	22	9
6.9. Reducing development cost	35	12 tie	22	10

*Adjusted Score Is "Gear Ratio" Multiplied
Adjusted Rank Based On Adjusted Score

Figure 8. Ares V Technology Priorities.

The "gear ratio" effect becomes significant, however, when the weight savings potential is weighted for the advantage offered by a specific element due to its position in the stack, e.g. the system weight multiplier for the lunar lander Ascent Stage is 18.3. This means that for every pound of weight saved in the Ascent Stage, 18.3 lb of system weight saving is realized. The resulting large difference in Consensus rank and Adjusted rank is evident in Figure 9. In this

Technology	Consensus Score	Consensus Rank	Adjusted Score*	Adjusted Rank*
7.6. Lunar polar extreme temperature fluctuations	65	22 tie	790	1
6.4. Structural health monitoring, diagnostics, and prognostics	124	1	765	2
6.9. Reducing development cost	123	2	725	3
6.1. Inspection Methods	98	4	614	4
7.2. Lunar dust impacts	50	40	611	5
3.11. In-space/ground repair methods	64	26 tie	611	6
5.8. Develop NDE standards	88	8	604	7
7.7. Radiation hardened structures	53	37 tie	594	8
4.4. Improved methods of analyzing highly tailored composites	66	20 tie	593	9
3.7. Primarily Bonded structures	86	9	587	10

*Adjusted Score Is "Gear Ratio" Multiplied
Adjusted Rank Based On Adjusted Score

Figure 9. Technology Ranking Across All Constellation Elements.

figure, some of the technologies identified as important for the Launch vehicles are not even in the running. Figure 10 illustrates the effect of this gear ratio weighted ranking in a side by side

Rank	ARES V
1	2.3. Manufacturing technologies for large scale structures
2	2.2. Scale up of manufacturing methods to large (33-ft dia) structures
3	2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures
4	5.1. Define damage tolerance requirements
5	2.1. Develop improved non-autoclave processes for traditional carbon/resin systems
6	4.1. Advanced analysis for composite shell structures considering imperfections, failure mechanisms

Rank	Across All Components
1	7.6. Lunar polar extreme temperature fluctuations
2	6.4. Structural health monitoring, diagnostics, and prognostics
3	6.9. Reducing development cost
4	6.1. Inspection Methods
5	7.2. Lunar dust impacts
6	3.11. In-space/ground repair methods

Lunar Element Technologies Dominate Due to the Large Multipliers At Upper End Of Stack

Figure 10. Influence of "Gear Ratio" Weighting on Technology Ranking.

comparison of Technology rankings for Ares V only versus the rankings derived from the Adjusted scores across all elements. The contrast in the technologies and the relevance to Lunar elements show that the Lunar element technologies dominate due to the large multipliers at the upper end of the stack.

Effect of Removing Technologies with No Effect on Element Weight

In examining the list of technology sub-categories, a select few were directed at support technology development. These sub-categories will not impact element weight and an attempt was made to filter them out and see if any other technologies thought to be significant would ascend in the ranks. As a first step in this filtering process, the technology sub-categories were flagged with respect to their potential for weight impact. A sample of the flagged technologies under Design Criteria and Allowables, and Development, Quality Assurance and Certification is shown in Figure 11. As seen in the figure sub-categories such as developing NDE standards are

Technologies	Weight Impact?
5.1. Define damage tolerance requirements	Yes
5.2. Radiation Protection	Yes
5.3. MMOD Resistant Design	Yes
5.4. Standardized Allowables such as MIL-HDBK-17 modifications	Yes
5.7. Develop and justify more reasonable safety factors based on aircraft approach	Yes
5.8. Develop NDE standards	No
5.9. Better understand and refine minimum gage specifications	Yes
5.10. Develop database for better understanding of damage	Yes
6.1. Inspection Methods	No
6.2. QA to Structural Performance Correlation	No
6.3. Post-Damage Reliability Prediction	Yes
6.4. Structural health monitoring, diagnostics, and prognostics	No
6.5. Establish Minimum complexity for design hot spot interrogation	Yes
6.6. Identify smallest test scale where full environmental (including in-space) simulation is required	No
6.9. Reducing development cost	No

Figure 11. Filter For Technologies that Do Not Directly Impact Structural Mass

not expected to yield any mass savings and have been flagged as such. The influence of removing "no mass impact" technologies from the overall "gear ratio" adjusted rankings is shown in Figure 12. Structural health monitoring, reducing development cost and inspection methods fall out of the top spots and are replaced by mass savings related technologies such as radiation hardened structures, improved methods of analyzing highly tailored composites, and primarily bonded structures.

Rank	Across All Elements
1	7.6. Lunar polar extreme temperature fluctuations
2	6.4. Structural health monitoring, diagnostics, and prognostics
3	6.9. Reducing development cost
4	6.1. Inspection Methods
5	7.2. Lunar dust impacts
6	3.11. In-space/ground repair methods

All Technologies

Rank	Across All Elements
1	7.6. Lunar polar extreme temperature fluctuations
2	7.2. Lunar dust impacts
3	3.11. In-space/ground repair methods
4	7.7. Radiation hardened structures
5	4.4. Improved methods of analyzing highly tailored composites
6	3.7. Primarily Bonded structures

Weight Impact Technologies Only

Figure 12. Effect of Filtering Out Technologies That Do Not Directly Reduce Mass

Technology Rankings

Based on the preceding discussion, and without applying the Mass Impact filter, the technologies shown in Figure 13 for each Constellation element emerged as top ranked. The red line across

Rank	Ares I/Orion
1	5.9. Better understand and refine minimum gage specifications
2	2.6. In-process inspection techniques and acceptance methodology
3	1.7. Long out-time/Long shelf-life materials
4 tie	5.8. Develop NDE standards
4 tie	7.1. MMOD protection (lunar/IEO)
6	6.4. Structural health monitoring, diagnostics, and prognostics
7	6.9. Reducing development cost
8 tie	6.7. Establish level of certification that can be accomplished by analysis
8 tie	6.3. Post-Damage Reliability Prediction
10	7.5. Static charge issues (on Earth or Moon)

Rank	Ares V
1	2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates
2	2.2. Scale up of manufacturing methods to large (33-ft dia) structures
3	2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures
4	5.1. Define damage tolerance requirements
5	2.1. Develop improved non-autoclave processes for traditional carbon/resin systems
6	4.1. Advanced analysis for composite shell structures considering imperfections, failure mechanisms
7	3.1. Efficient bolted or bonded joints between large sections
8	5.8. Develop NDE standards
9	3.3. Sandwich Designs
10	6.9. Reducing development cost

Rank	Lunar Lander
1	3.16. Crashworthiness incorporated in design
2 tie	6.1. Inspection Methods
2 tie	6.4. Structural health monitoring, diagnostics, and prognostics
4	5.8. Develop NDE standards
5	7.6. Lunar polar extreme temperature fluctuations
6	4.4. Improved methods of analyzing highly tailored composites
7	3.7. Primarily Bonded structures
8	6.9. Reducing development cost
9	7.1. MMOD protection (lunar/IEO)
10 tie	1.4. Co-cure, co-bond, and secondary bond process characterization for repeatable production of bonded structures
10 tie	2.5. Vented core and core splicing technology development
10 tie	3.3. Sandwich Designs

Rank	Lunar Habitat
1	7.6. Lunar polar extreme temperature fluctuations
2	7.4. Aging in lunar environment
3 tie	3.11. In-space/ground repair methods
3 tie	4.5. Simulated test and evaluation of structural designs
5 tie	4.4. Improved methods of analyzing highly tailored composites
5 tie	6.9. Reducing development cost
5 tie	7.2. Lunar dust impacts
5 tie	7.9. Coatings and sealants
9 tie	4.3. Effects of defects in novel design concepts, e.g., missing stitches, local debonds, porousity
9 tie	4.7. Failure mechanism/prediction at RT or extreme temperatures
9 tie	5.2. Radiation Protection
9 tie	5.10. Develop database for better understanding of damage
9 tie	6.4. Structural health monitoring, diagnostics, and prognostics

Rank	Lunar Mobility
1	7.6. Lunar polar extreme temperature fluctuations
2 tie	4.5. Simulated test and evaluation of structural designs
2 tie	7.4. Aging in lunar environment
4	7.2. Lunar dust impacts
5 tie	3.5. Hybrid (metal/Composite) stiffened structures
5 tie	3.11. In-space/ground repair methods
5 tie	6.4. Structural health monitoring, diagnostics, and prognostics
5 tie	6.9. Reducing development cost
9	3.9. Point load introduction
10	5.10. Develop database for better understanding of damage

Figure 13. Top Ranked Technologies for Each Individual Constellation Element.

the five tables delineates the top 5 for each element. For clarity, the individual element boxes in Figure 13 are expanded and shown in Figures 14 through 18.

Rank	Ares I/Orion
1	5.9. Better understand and refine minimum gage specifications
2	2.6. In-process inspection techniques and acceptance methodology
3	1.7. Long out-time/Long shelf-life materials
4 tie	5.8. Develop NDE standards
4 tie	7.1. MMOD protection (lunar/lEO)
6	6.4. Structural health monitoring, diagnostics, and prognostics
7	6.9. Reducing development cost
8 tie	6.7. Establish level of certification that can be accomplished by analysis
8 tie	6.3. Post-Damage Reliability Prediction
10	7.5. Static charge issues (on Earth or Moon)

Figure 14. Ares I/Orion Technology Priorities.

Rank	Ares V
1	2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates
2	2.2. Scale up of manufacturing methods to large (33-ft dia) structures
3	2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures
4	5.1. Define damage tolerance requirements
5	2.1. Develop improved non-autoclave processes for traditional carbon/resin systems
6	4.1. Advanced analysis for composite shell structures considering imperfections, failure mechanisms
7	3.1. Efficient bolted or bonded joints between large sections
8	5.8. Develop NDE standards
9	3.3. Sandwich Designs
10	6.9. Reducing development cost

Figure 15. Ares V Technology Priorities.

Rank	Lunar Lander
1	3.16. Crashworthiness incorporated in design
2 tie	6.1. Inspection Methods
2 tie	6.4. Structural health monitoring, diagnostics, and prognostics
4	5.8. Develop NDE standards
5	7.6. Lunar polar extreme temperature fluctuations
6	4.4. Improved methods of analyzing highly tailored composites
7	3.7. Primarily Bonded structures
8	6.9. Reducing development cost
9	7.1. MMOD protection (lunar/IEO)
10 tie	1.4. Co-cure, co-bond, and secondary bond process characterization for repeatable production of bonded structures
10 tie	2.5. Vented core and core splicing technology development
10 tie	3.3. Sandwich Designs

Figure 16. Lunar Lander Technology Priorities.

Rank	Lunar Habitat
1	7.6. Lunar polar extreme temperature fluctuations
2	7.4. Aging in lunar environment
3 tie	3.11. In-space/ground repair methods
3 tie	4.5. Simulated test and evaluation of structural designs
5 tie	4.4. Improved methods of analyzing highly tailored composites
5 tie	6.9. Reducing development cost
5 tie	7.2. Lunar dust impacts
5 tie	7.9. Coatings and sealants
9 tie	4.3. Effects of defects in novel design concepts, e.g., missing stitches, local debonds, porousity
9 tie	4.7. Failure mechanism/prediction at RT or extreme temperatures
9 tie	5.2. Radiation Protection
9 tie	5.10. Develop database for better understanding of damage
9 tie	6.4. Structural health monitoring, diagnostics, and prognostics

Figure 17. Lunar Habitat Technology Priorities.

Rank	Lunar Mobility
1	7.6. Lunar polar extreme temperature fluctuations
2 tie	4.5. Simulated test and evaluation of structural designs
2 tie	7.4. Aging in lunar environment
4	7.2. Lunar dust impacts
5 tie	3.5. Hybrid (metal/Composite) stiffened structures
5 tie	3.11. In-space/ground repair methods
5 tie	6.4. Structural health monitoring, diagnostics, and prognostics
5 tie	6.9. Reducing development cost
9	3.9. Point load introduction
10	5.10. Develop database for better understanding of damage

Figure 18. Lunar Mobility Technology Priorities.

Figure 19 below compares the Ares V technology priorities derived from the methodology applied in this task with the prioritization in Ref. 5. As can be seen in the figure, the results of the present study are corroborated by the Ref. 5 recommendations to focus Ares V technology development on large scale composite structures.

Ares Project Office Major Prioritized Technology Needs

1. Large Composite Manufacturing
2. HTPB Propellant
3. Long-term Cryogenic Storage
4. Composite damage tolerance/detection
5. EDS state determination/abort
5. Composite joining technology
7. Liquid Level Measurement
8. Multi-layer Insulation
9. Leak detection
10. Non autoclave composites
10. SRM composite metal technology
12. Develop composite dry structures
13. Composite damage failure detection for abort and damage identification
14. Composite Nozzle NDE
15. Nozzle sensitivity to pocketing/ ply lifting using HTPB with higher heat flux
16. TVC architecture development to minimize operations (EHA Ares I upgrade)
17. Detection of micro cracking in hydrogen tank (composites)

Rank	Ares V
1	2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates
2	2.2. Scale up of manufacturing methods to large (33-ft dia) structures
3	2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures
4	5.1. Define damage tolerance requirements
5	2.1. Develop improved non-autoclave processes for traditional carbon/resin systems
6	4.1. Advanced analysis for composite shell structures considering imperfections, failure mechanisms
7	3.1. Efficient bolted or bonded joints between large sections
8	5.8. Develop NDE standards
9	3.3. Sandwich Designs
10	6.9. Reducing development cost

Figure 19. Comparison of Ares V Technology Priorities Developed in this Task with those Developed by NASA MSFC (Ref 5).

Technology Priorities

With the preceding discussion showing that the "gear ratio" multiplier effect is overwhelmingly in favor of Lunar elements and applying a mass impact filtering criterion can remove some key technologies from contention, the following criteria were used to select and recommend composites technologies for further development:

1. Select one top technology for each Constellation Program Element studied in this task.
2. Select technologies that are in the top 10 spots for any element AND apply to multiple elements
3. At least one technology from each of the seven major composite materials, structures and manufacturing technologies must be included

Application of these criteria to the element by element ranked technology list of Figure 13 , resulted in the top ranked technologies shown in Figure 20. This list forms the basis of recommendations in the next section.

Rank	Top Technologies
1, Habitat, Mobility & Multi	7.6. Lunar polar extreme temperature fluctuations
2 & Multi	6.4. Structural health monitoring, diagnostics, and prognostics
3 & Multi	6.9. Reducing development cost
4	6.1. Inspection Methods
5 & Multi	7.2. Lunar dust impacts
Ares I/Orion	5.9. Better understand and refine minimum gage specifications
Ares V	2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates
Lunar Lander	3.16. Crashworthiness incorporated in design
6 & Multi	3.11. In-space/ground repair methods
14 & Multi	4.5. Simulated test and evaluation of structural designs
26 & Multi	7.4. Aging in lunar environment
Top Ranked in M&P*	1.4. Co-cure, co-bond, and secondary bond process characterization for repeatable production of bonded structures

Figure 20. Prioritized List of Composites Technologies that Need to Be Developed to Enable or Enhance Project Constellation Element Structures

Technology Roadmaps

Once the technology development priorities have been established, each top ranked technology needs to be evaluated for its current TRL, calendar time available to advance the TRL to 6, the degree of difficulty associated with this advancement and the risks that need to be mitigated to reach the desired TRL. A preliminary effort was made to address these issues by way of defining a degree-of-difficulty category, and a rudimentary (because a rigorous roadmap requires a thorough technology assessment) roadmap. A simple approach to characterizing the degree of difficulty is illustrated in Figure 21 where degree of difficulty categories are assigned based on the estimated time required to reach TRL 6 and the resources in equivalent dollars required to advance the technology to that level. These categories were used as labels on each roadmap to characterize the degree of difficulty associated with accomplishing the objectives of the roadmap.

Category	Years to TRL 6	$, M
1	0-5	<2
2	0-5	<5
3	0-5	<10
4	0-5	<100
5	5-10	>100

Figure 21. Degree of Difficulty Categories

Preliminary roadmaps were developed for eight of the twelve technologies listed in Figure 20. The four technologies that were not depicted in roadmaps were reducing development cost, inspection methods, simulated test and design of structural designs and aging in lunar environments would have required additional studies not within the scope of this effort. All eight roadmaps are shown in APPENDIX C.

An example using technology sub-category 2.3- Manufacturing Technologies for Large Scale Structures is illustrated in Figure 22 below. The roadmap shows a sequence of technical activities structured in a "building block" fashion that need to be accomplished by PDR for Ares V at end of 2012 and the accompanying increase in TRL as select events in the roadmap result in mitigation of specific risks. The color coded activity bands show the suggested funding sources. The degree of difficulty assigned to this road map is Category 4.

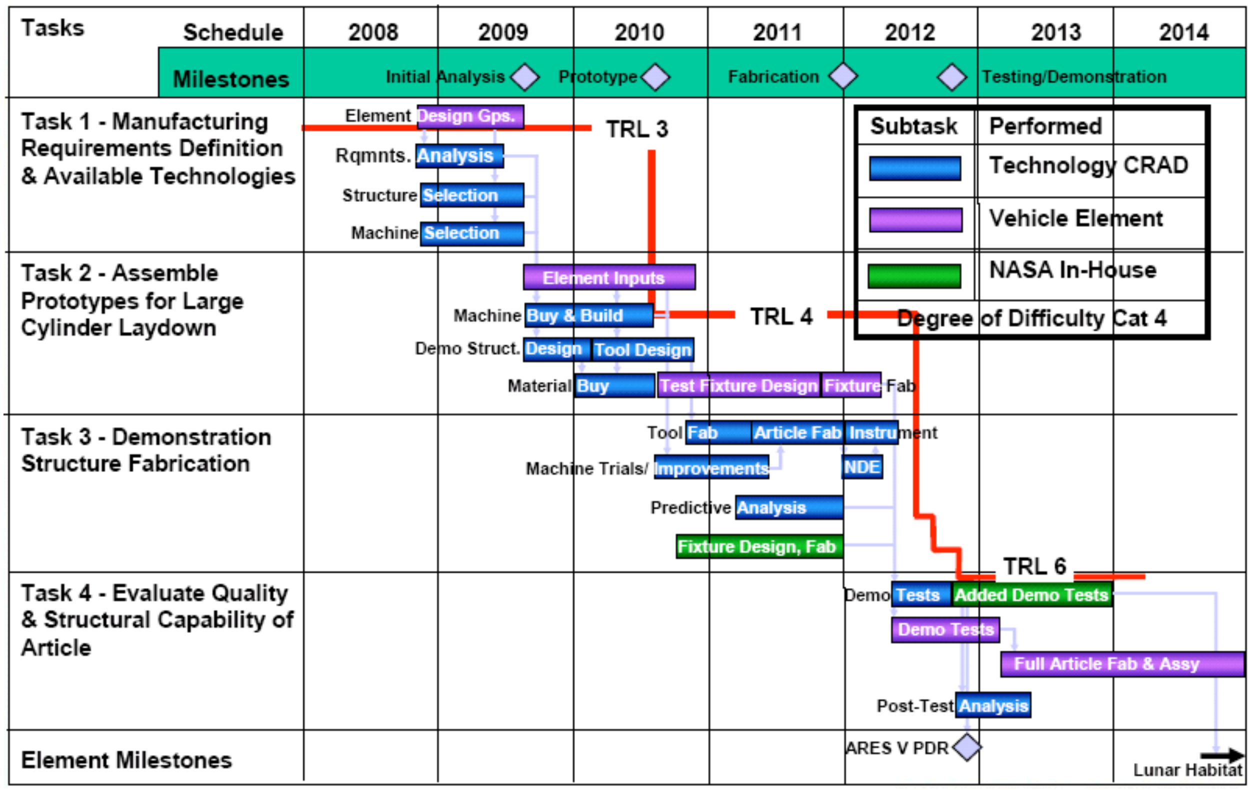


Figure 22. Example Roadmap for Large Scale Structures Manufacturing Technologies, Illustrating Key Events, and Advances in TRL Time Sequenced to Key Program Milestones.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results presented in preceding sections, the following conclusions and recommendations are presented.

Conclusions

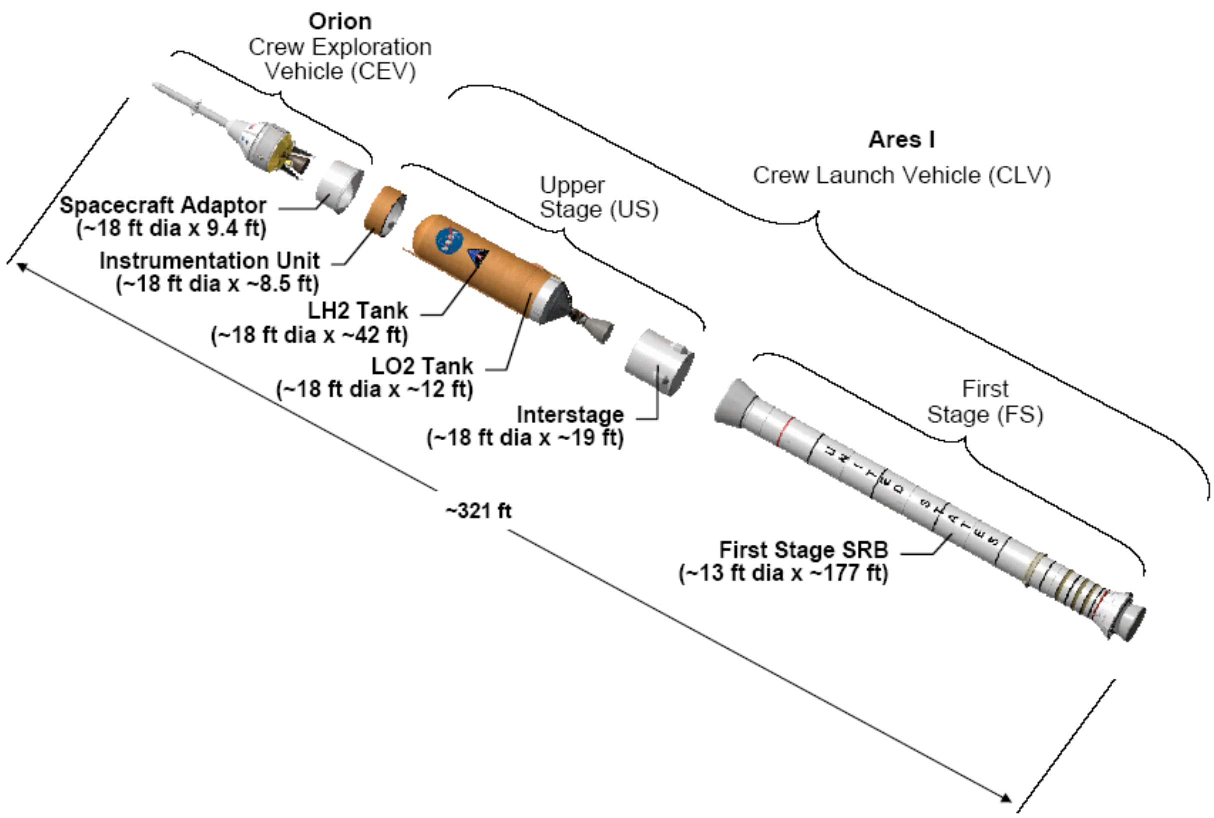
1. Composite structures, materials, and manufacturing technologies with the highest potential for mass savings in Vison for Space Exploration Structures have been identified. A rank ordered list of these technologies is shown in Figure 20.
2. Preliminary technology development roadmaps with the TRL advancement events outlined and the degree of difficulty estimated have been prepared for eight of the twelve recommended technologies.

Recommendations

1. Develop detailed resource loaded roadmaps for the recommended technologies, and estimate ROM technology development costs
2. Initiate technology development activities for Ares V, Lunar Lander, Lunar Habitat, and Lunar Surface Mobility elements immediately to achieve a TRL of 6 by their respective PDRs.

APPENDIX A
Exploration Vehicle Baseline Configurations

The figures in this APPENDIX show baseline configurations for the Constellation elements used in the technology trade studies.



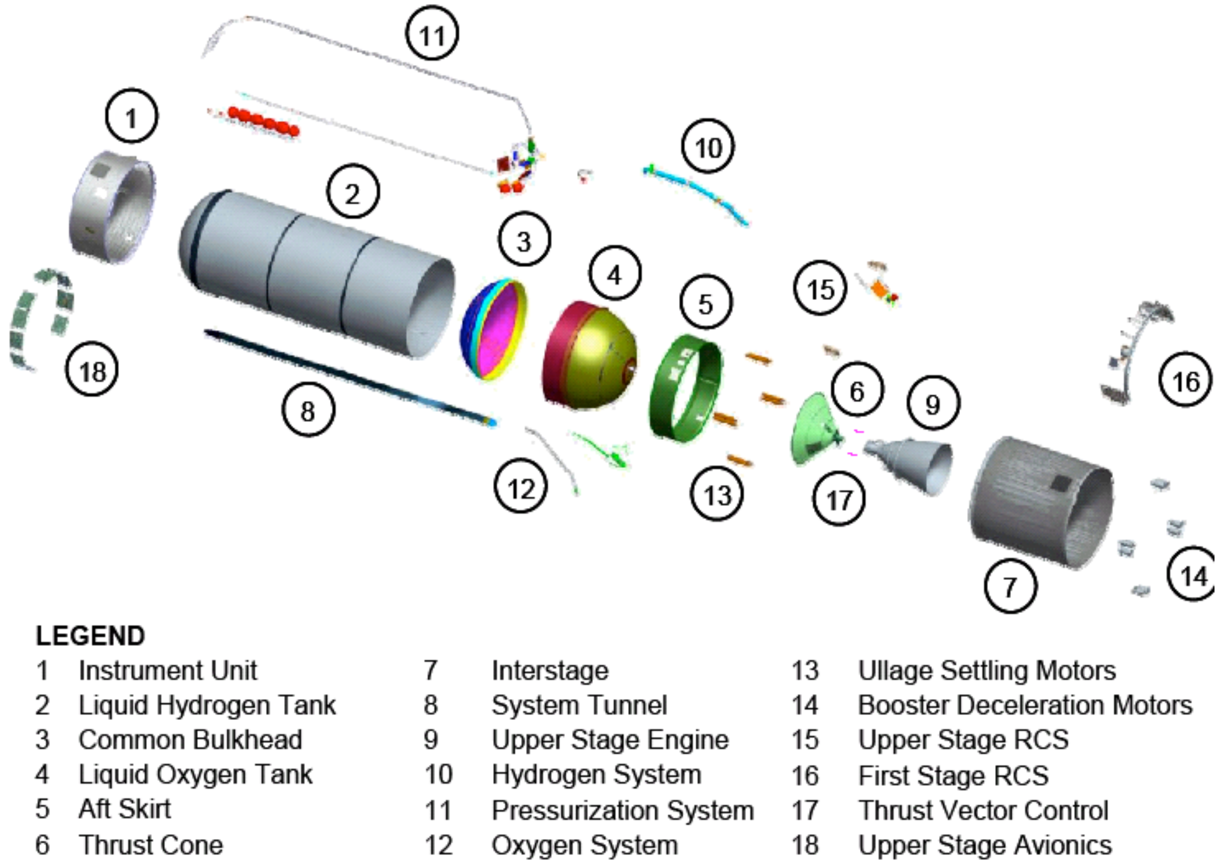


Figure A.2 ARES I UPPER STAGE MAJOR ELEMENTS (Ref. 2)

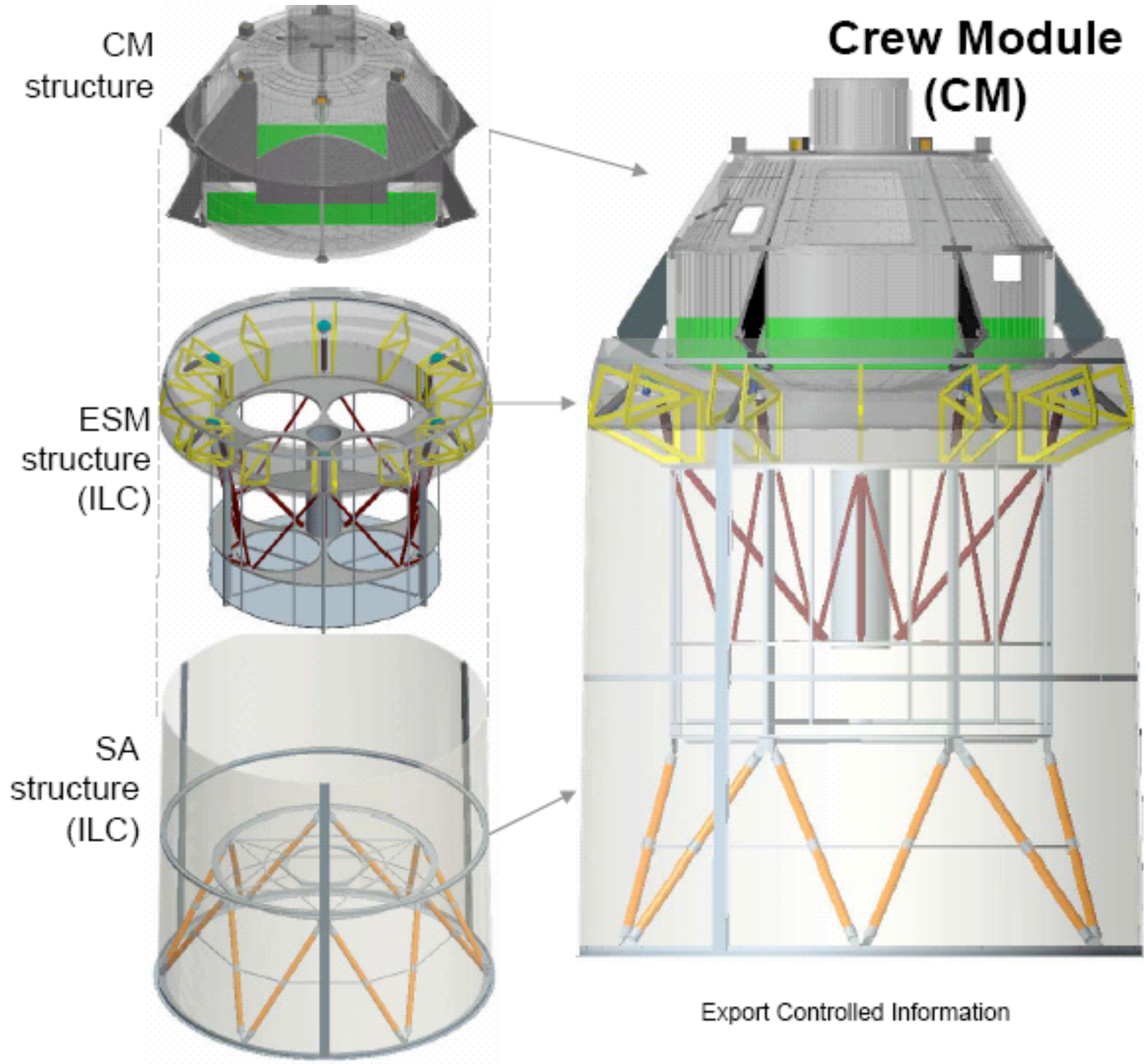


Figure A.3 ORION CREW MODULE AND SERVICE MODULE

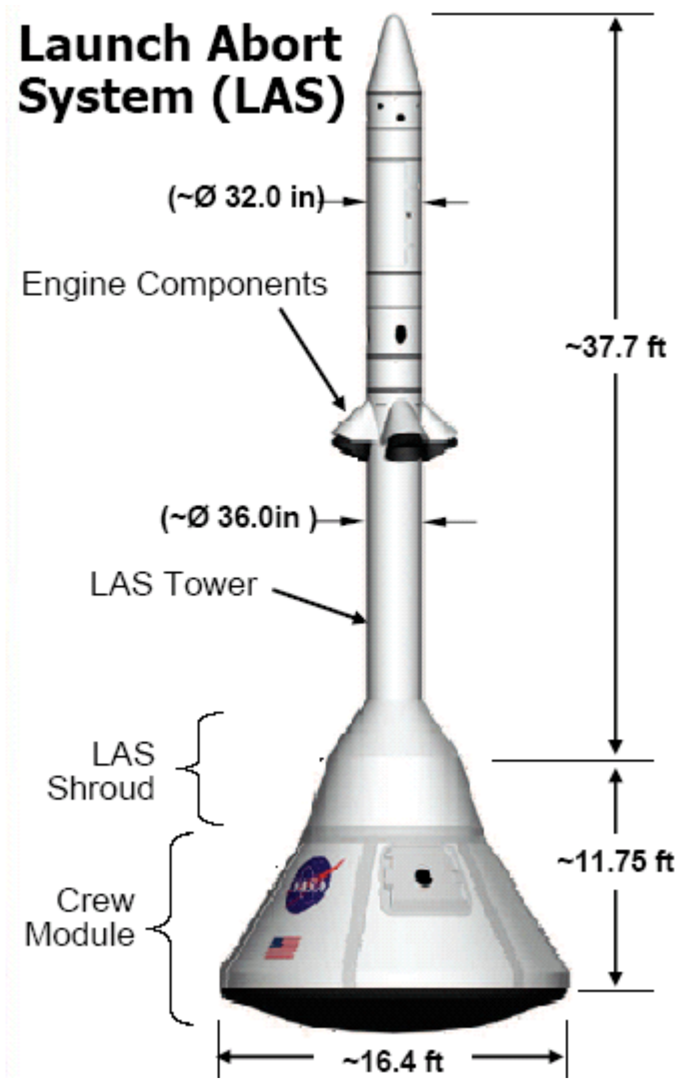


Figure A.4 LAUNCH ABORT SYSTEM

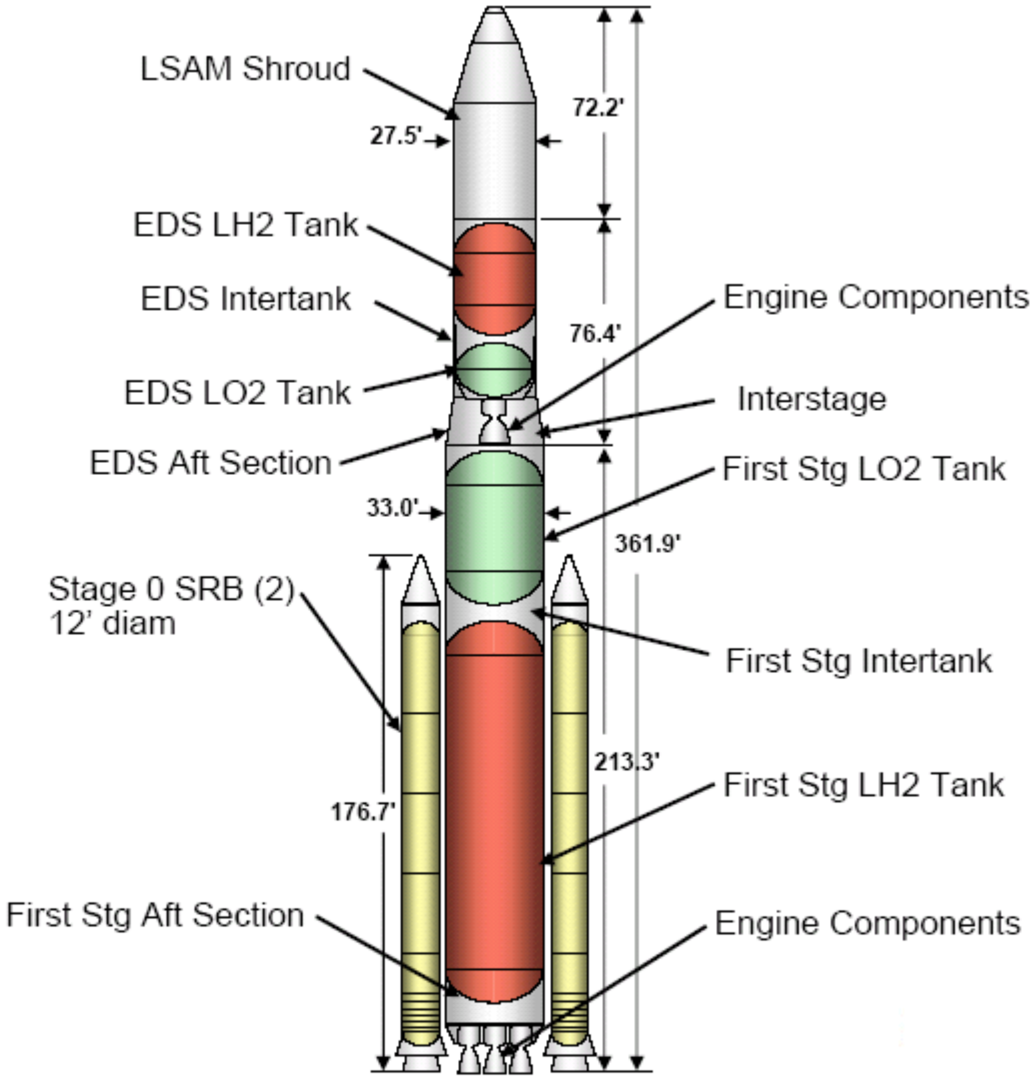


Figure A.5 ARES V CARGO LAUNCH VEHICLE

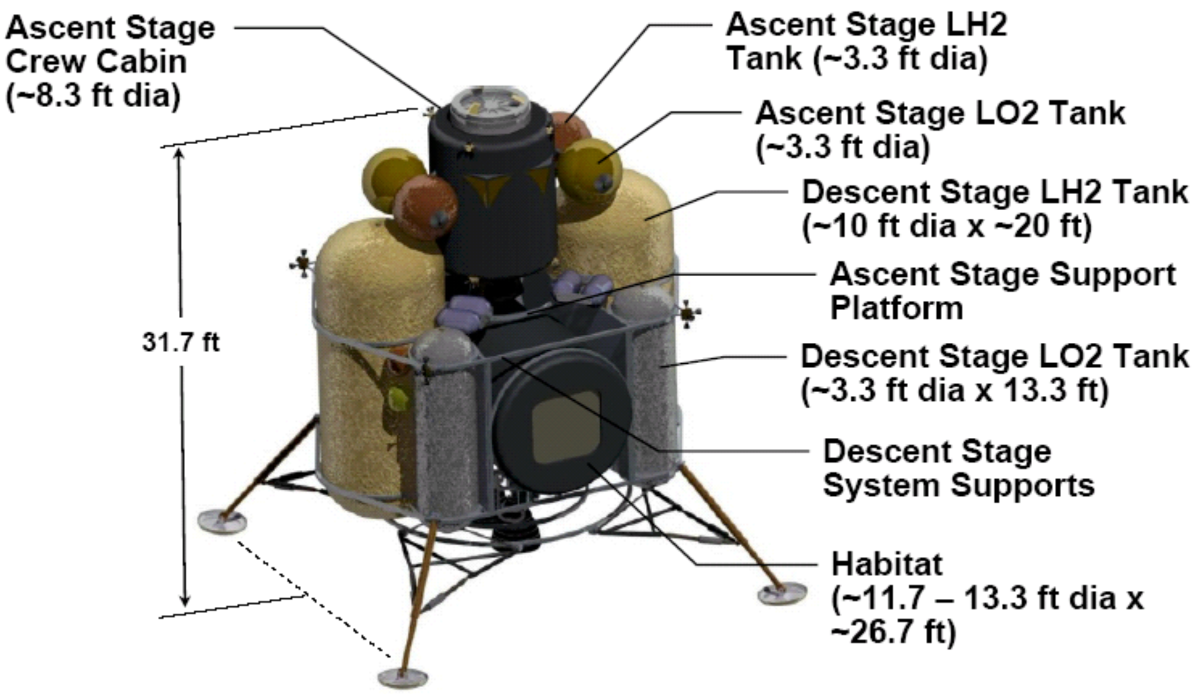


Figure A.5 LUNAR LANDER

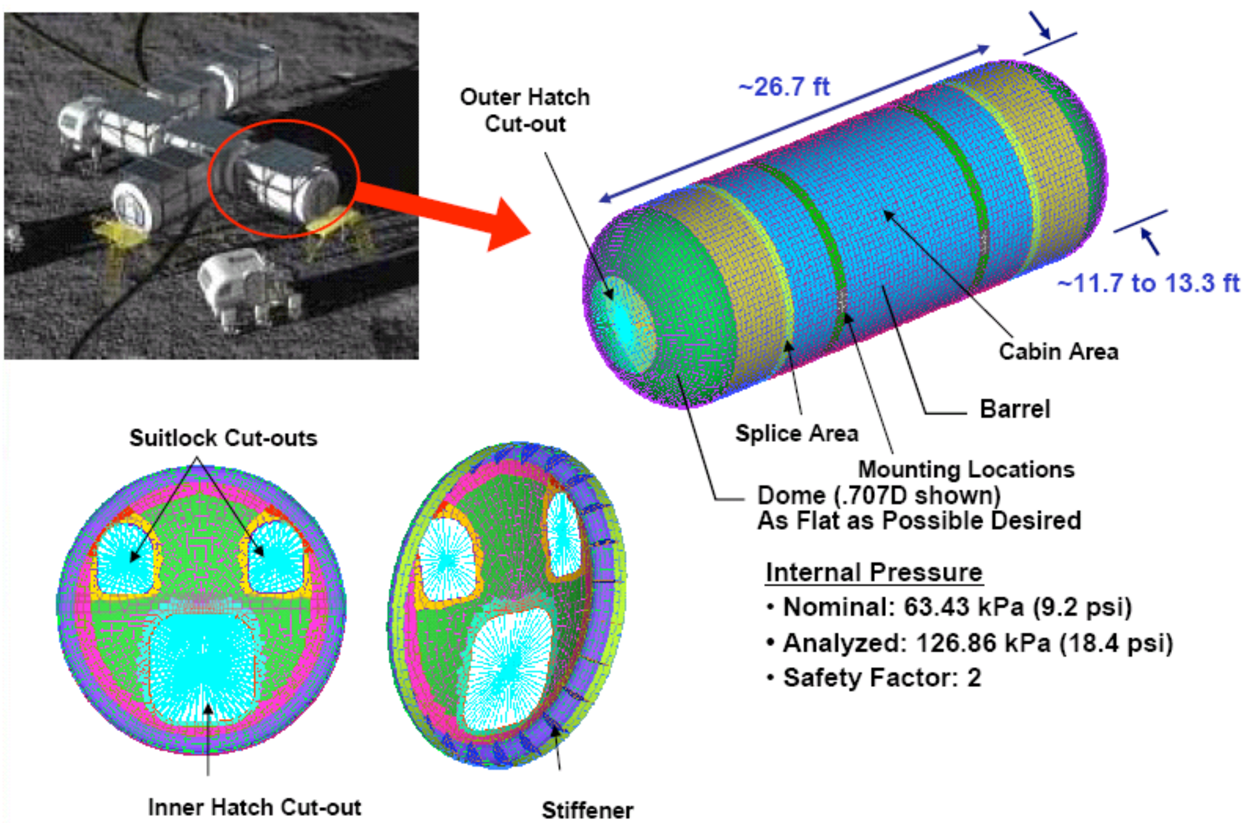
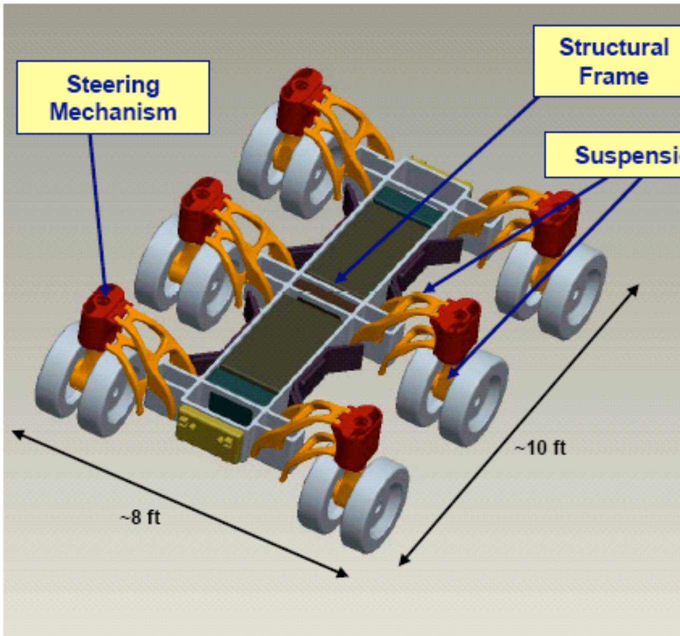


Figure A.6 LUNAR SURFACE SYSTEMS, LUNAR HABITAT



Lunar Rover Concepts

Figure A.7 LUNAR SURFACE SYSTEMS, LUNAR HABITAT

APPENDIX B
Composites Technologies and Element Structural Sub-Components

The following seven figures show the composites technologies that were identified by NASA-Industry consensus as having the potential to significantly impact CxP element structures. The column headers in the spreadsheets show the technology sub-categories that were evaluated. The rows show the CxP elements and their decomposition into structural sub-component

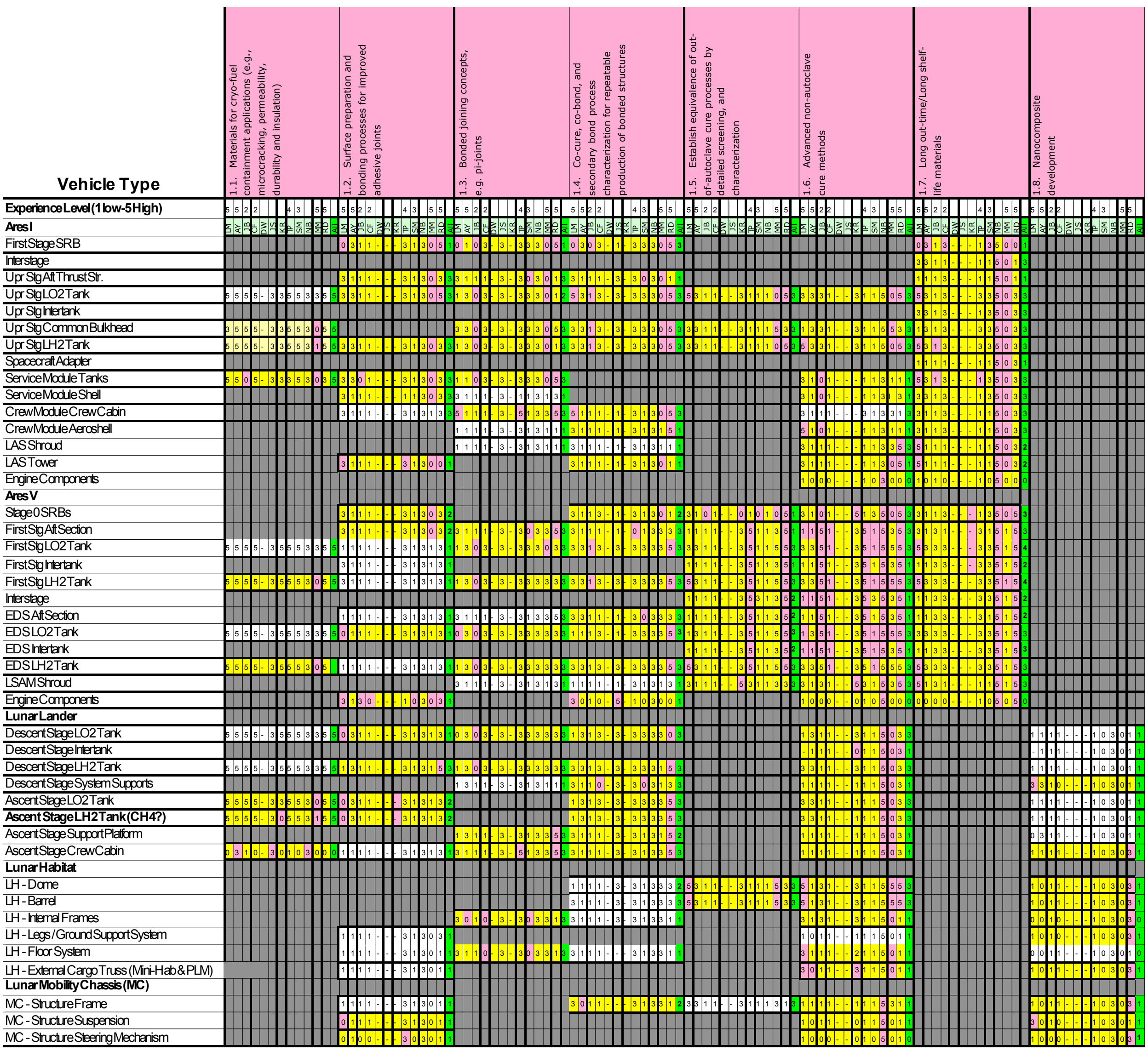


Figure B.1 Materials and Processes Technology Sub-Categories

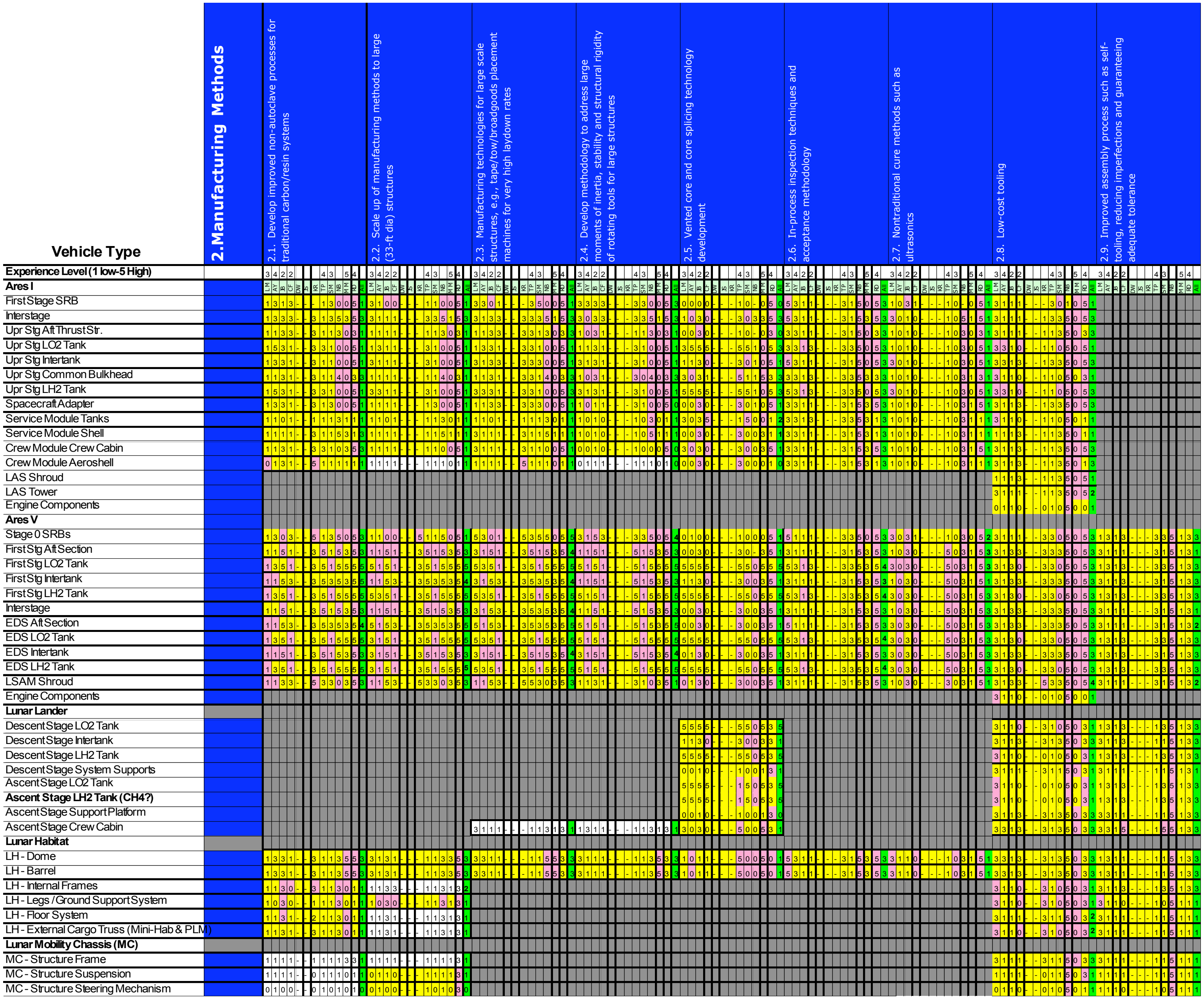


Figure B.2 Manufacturing Technology Sub-Categories

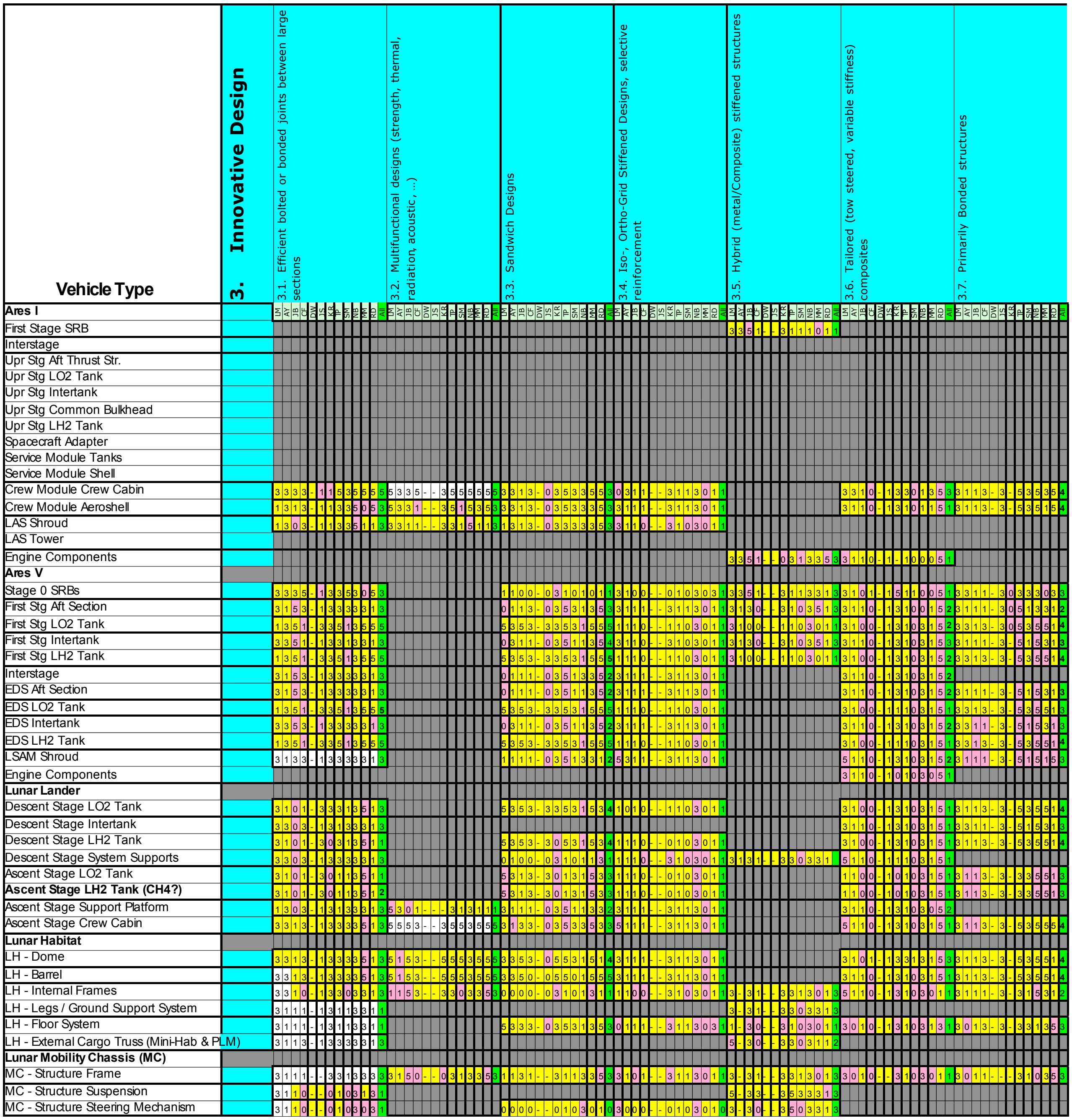


Figure B.3 Innovative Design Technology Sub-Categories

3.8. Stitched Designs

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	HM	RD	All
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin	1	1	1	0	-	-	-	1	0	3	0	1	1
Crew Module Aeroshell	3	1	1	0	-	-	-	1	0	3	0	1	1
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs													
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank													
EDS Intertank													
EDS LH2 Tank													
LSAM Shroud													
Engine Components													
Lunar Lander													
Descent Stage LO2 Tank	1	1	0	0	-	-	-	1	0	3	0	1	1
Descent Stage Intertank	3	1	1	0	-	-	-	1	0	3	0	1	1
Descent Stage LH2 Tank	1	1	0	0	-	-	-	1	0	3	0	1	1
Descent Stage System Supports													
Ascent Stage LO2 Tank	0	1	0	0	-	-	-	1	0	3	0	1	1
Ascent Stage LH2 Tank (CH4?)	0	1	0	0	-	-	-	1	0	3	0	1	1
Ascent Stage Support Platform													
Ascent Stage Crew Cabin	3	3	1	0	-	-	-	1	0	3	0	1	1
Lunar Habitat													
LH - Dome	3	0	0	0	-	-	-	1	0	3	0	1	1
LH - Barrel	3	0	0	0	-	-	-	1	0	3	0	1	1
LH - Internal Frames	3	0	1	0	-	-	-	1	0	3	0	1	1
LH - Legs / Ground Support System													
LH - Floor System	1	0	1	0	-	-	-	1	0	3	0	1	1
LH - External Cargo Truss (Mini-Hab & PLM)													
Lunar Mobility Chassis (MC)													
MC - Structure Frame	3	0	1	0	-	-	-	1	0	3	0	1	1
MC - Structure Suspension													
MC - Structure Steering Mechanism													

3.9. Point load introduction

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	HM	RD	All
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin	1	1	1	1	-	3	3	3	1	5	3	5	3
Crew Module Aeroshell	1	1	1	1	-	3	3	3	1	5	1	1	1
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs	3	1	1	3	-	3	3	3	3	5	3	5	3
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage	1	1	1	1	-	3	-	3	1	5	0	3	2
EDS Aft Section	3	1	3	1	-	3	-	3	1	5	0	5	3
EDS LO2 Tank	1	1	1	3	-	3	-	3	3	5	0	5	3
EDS Intertank	1	1	1	1	-	3	-	3	1	5	0	5	2
EDS LH2 Tank	1	1	1	3	-	3	-	3	3	5	0	5	3
LSAM Shroud	1	1	3	1	-	3	-	3	1	5	0	1	1
Engine Components													
Lunar Lander													
Descent Stage LO2 Tank	1	1	1	3	-	3	3	3	3	5	0	3	3
Descent Stage Intertank	3	1	1	1	-	3	3	3	1	5	0	3	2
Descent Stage LH2 Tank	1	1	1	3	-	3	3	3	3	5	0	3	3
Descent Stage System Supports	5	1	3	1	-	3	3	3	1	5	3	3	3
Ascent Stage LO2 Tank	1	1	1	3	-	3	0	1	3	5	0	3	1
Ascent Stage LH2 Tank (CH4?)	1	1	1	3	-	3	0	1	3	5	0	3	1
Ascent Stage Support Platform	3	1	3	1	-	3	3	3	1	5	3	3	3
Ascent Stage Crew Cabin	1	1	3	1	-	3	3	3	1	5	0	3	3
Lunar Habitat													
LH - Dome	1	1	1	1	-	3	1	3	1	5	0	3	1
LH - Barrel	1	1	1	1	-	3	1	3	1	5	0	3	1
LH - Internal Frames	1	0	3	1	-	3	1	3	1	5	0	3	3
LH - Legs / Ground Support System	3	0	3	1	-	3	1	3	0	5	0	3	2
LH - Floor System	1	0	3	1	-	3	1	3	1	5	0	3	2
LH - External Cargo Truss (Mini-Hab & PLM)	3	0	3	1	-	3	1	3	1	5	0	3	3
Lunar Mobility Chassis (MC)													
MC - Structure Frame	1	0	3	1	-	-	1	3	1	5	3	3	2
MC - Structure Suspension	3	0	3	1	-	-	1	3	1	5	3	3	3
MC - Structure Steering Mechanism	3	0	3	1	-	-	1	3	1	5	3	1	2

3.10. Inflatables

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	HM	RD	All
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin													
Crew Module Aeroshell													
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs													
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank													
EDS Intertank													
EDS LH2 Tank													
LSAM Shroud													
Engine Components													
Lunar Lander													
Descent Stage LO2 Tank													
Descent Stage Intertank													
Descent Stage LH2 Tank													
Descent Stage System Supports													
Ascent Stage LO2 Tank													
Ascent Stage LH2 Tank (CH4?)													
Ascent Stage Support Platform													
Ascent Stage Crew Cabin													
Lunar Habitat													
LH - Dome	1	1	3	1	-	-	5	3	0	0	5	5	2
LH - Barrel	1	1	3	1	-	-	5	3	0	0	5	5	2
LH - Internal Frames	0	1	3	0	-	-	5	3	0	0	5	5	3
LH - Legs / Ground Support System													
LH - Floor System													
LH - External Cargo Truss (Mini-Hab & PLM)													
Lunar Mobility Chassis (MC)													
MC - Structure Frame	0	1	0	0	-	-	0	1	0	0	0	1	0
MC - Structure Suspension													
MC - Structure Steering Mechanism													

3.11. In-space/ground repair methods

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	HM	RD	All
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin	3	3	1	3	-	-	-	3	3	5	3	5	3
Crew Module Aeroshell	3	3	3	3	-	-	-	3	0	5	3	5	3
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs													
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank													
EDS Intertank													
EDS LH2 Tank													
LSAM Shroud													
Engine Components													
Lunar Lander													
Descent Stage LO2 Tank	3	3	0	1	-	-	-	1	1	3	0	5	2
Descent Stage Intertank	1	3	0	0	-	-	-	1	0	3	0	5	1
Descent Stage LH2 Tank	3	3	0	1	-	-	-	1	1	3	0	5	3
Descent Stage System Supports	3	3	0	1	-	-	-	1	1	3	0	5	3
Ascent Stage LO2 Tank	3	3	0	1	-	-	-	1	1	3	1	5	2
Ascent Stage LH2 Tank (CH4?)	3	3	0	1	-	-	-	1	1	3	1	5	2
Ascent Stage Support Platform	3	3	0	1	-	-	-	1	1	3	1	5	2
Ascent Stage Crew Cabin	5	3	3	3	-	-	-	3	3	5	3	5	3
Lunar Habitat													
LH - Dome	5	3	5	3	-	-	-	3	3	1	5	3	4
LH - Barrel	5	3	5	3	-	-	-	3	3	5	5	3	4
LH - Internal Frames	3	3	3	1	-	-	-	3	1	1	5	3	3
LH - Legs / Ground Support System	3	1	3	1	-	-	-	3	1	1	5	3	3
LH - Floor System	3	1	5	1	-	-	-	3	1	1	5	3	3
LH - External Cargo Truss (Mini-Hab & PLM)	5	1	5	1	-	-	-	3	1	1	5	3	4
Lunar Mobility Chassis (MC)													
MC - Structure Frame	3	3	5	1	-	-	-	3	1	1	5	3	3
MC - Structure Suspension	3	1	5	1	-	-	-	3	0	1	5	3	3
MC - Structure Steering Mechanism	3	1	5	1	-	-	-	3	0	1	5	3	3

3.12. Nanocomposites for load bearing applications and reduce damage growth

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	HM	RD	All
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin													
Crew Module Aeroshell													
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs													
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank													
EDS Intertank													
EDS LH2 Tank													
LSAM Shroud													
Engine Components													
Lunar Lander													
Descent Stage LO2 Tank													
Descent Stage Intertank	3	1	1	0	-	-	-	1	0	-	-	1	1
Descent Stage LH2 Tank													
Descent Stage System Supports	3	1	1	0	-	-	-	1	0	-	-	1	1
Ascent Stage LO2 Tank													
Ascent Stage LH2 Tank (CH4?)													
Ascent Stage Support Platform													
Ascent Stage Crew Cabin	5	1	1	1	-	-	-	1	0	-	-	1	1
Lunar Habitat													
LH - Dome													
LH - Barrel													
LH - Internal Frames	3	0	1	0	-	-	-	1	0	-	0	1	1
LH - Legs / Ground Support System	3	0	1	0	-	-	-	1	0	-	0	1	1
LH - Floor System													
LH - External Cargo Truss (Mini-Hab & PLM)	5	0	1	1	-	-	-	1	0	0	0	1	1
Lunar Mobility Chassis (MC)													
MC - Structure Frame													
MC - Structure Suspension	5	0	1	0	-	-	-	1	0	-	-	1	1
MC - Structure Steering Mechanism	5	0	1	0	-	-	-	1	0	-	-	0	1

3.13. Nanocomposites for non-load bearing applications such as electrical, IVHM, thermal

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	HM	RD	All
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin	5	3	1	1	-	-	-	1	1	3	0	1	1
Crew Module Aeroshell	5	0	1	1	-	-	-	1	0	3	0	1	1
LAS Shroud	3	0	0	1	-	-	-	1	0	3	0	1	1
LAS Tower	3	1	0	1	-	-	-	1	0	3	0	1	1
Engine Components													
Ares V													
Stage 0 SRBs	3	1	1	1	-	-	-	1	0	3	0	1	1
First Stg Aft Section	3	1	1	1	-	-	-	1	0	3	0	1	1
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage	3	1	1	1	-	-	-	1	0	3	0	1	1
EDS Aft Section	3	1	1	1	-	-	-	1	0	3	0	1	1
EDS LO2 Tank													
EDS Intertank	3	1	1	1	-	-	-	1	0	3	0	1	1
EDS LH2 Tank													
LSAM Shroud													
Engine Components	5	3	0	1	-	-	-	1	1	3	0	1	1
Lunar Lander													
Descent Stage LO2 Tank													
Descent Stage Intertank													
Descent Stage LH2 Tank													
Descent Stage System Supports													
Ascent Stage LO2 Tank													
Ascent Stage LH2 Tank (CH4?)													
Ascent Stage Support Platform													
Ascent Stage Crew Cabin	5	3	1	1	-	-	-	1	1	3	0	1	1
Lunar Habitat													
LH - Dome	3	0	1	1	-	-	-	1	1	3	0	1	1
LH - Barrel	3	0	1	1	-	-	-	1	1	3	0	1	1
LH - Internal Frames	3	0	1	0	-	-	-	1	0	3	0	1	1
LH - Legs / Ground Support System	3	0	1	0	-	-	-	1	0	3	0	1	1
LH - Floor System	3	0	1	1	-	-	-	1	1	3	0	1	1
LH - External Cargo Truss (Mini-Hab & PLM)	5	0	1	1	-	-	-	1	0	3	0	1	1
Lunar Mobility Chassis (MC)													
MC - Structure Frame	3	0	1	0	-	-	-	1	0	3	0	1	1
MC - Structure Suspension	3	0	1	0	-	-	-	1	0	3	0	1	1
MC - Structure Steering Mechanism	3	0	1	0	-	-	-	1	0	3	0	5	3

3.14. Very high temperature capability as needed for engines and on reentry

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	HM	RD	All
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin	5	1	0	0	-	-	3	1	0	5	0	5	3
Crew Module Aeroshell	5	1	5	1	-	-	3	1	0	5	3	5	4
LAS Shroud													
LAS Tower													
Engine Components	5	3	5	3	-	-	0	3	3	5	5	5	5
Ares V													
Stage 0 SRBs	3	0	1	0	-	-	5	1	0	0	0	1	1
First Stg Aft Section	3	0	1	1	-	-	0	1	0	0	0	1	1
First Stg LO2 Tank	3	0	0	0	-	-	0	1	0	0	0	1	0
First Stg Intertank	1	0	1	0	-	-	0	1	0	0	0	1	0
First Stg LH2 Tank	3	0	0	0	-	-	0	1	0	0	0	1	0
Interstage	1	0	1	0	-	-	0	1	0	0	0	1	0
EDS Aft Section	3	0	1	1	-	-	0	1	0	0	0	1	1
EDS LO2 Tank	1	0	0	0	-	-	0	1	0	0	0	1	0
EDS Intertank	1	0	1	0	-	-	0	1	0	0	0	1	0
EDS LH2 Tank	1	0	0	0	-	-	0	1	0	0	0	1	0
LSAM Shroud	5	0	1	0	-	-	0	1	0	0	0	1	1
Engine Components	5	3	5	3	-	-	5	3	3	0	5	1	4
Lunar Lander													
Descent Stage LO2 Tank	1	1	0	0	-	-	0	1	0	0	0	1	0
Descent Stage Intertank	1	1	1	0	-	-	0	1	0	0	0	1	1
Descent Stage LH2 Tank	1	1	0	0	-	-	0	1	0	0	0	1	0
Descent Stage System Supports	3	1	1	0	-	-	0	1	0	0	0	1	1
Ascent Stage LO2 Tank	1	1	0	0	-	-	0	1	0	0	0	1	0
Ascent Stage LH2 Tank (CH4?)	1	1	0	0	-	-	0	1	0	0	0	1	0
Ascent Stage Support Platform	1	1	1	0	-	-	0	5	0	0	0	1	1
Ascent Stage Crew Cabin	5	1	0	0	-	-	0	3	0	0	0	1	1
Lunar Habitat													
LH - Dome	3	0	1	0	-	-	0	1	0	0	0	1	1
LH - Barrel	3	0	1	0	-	-	0	1	0	0	0	1	1
LH - Internal Frames	0	0	1	0	-	-	0	1	0	0	0	1	0
LH - Legs / Ground Support System	0	0	1	0	-	-	0	1	0	0	0	1	0
LH - Floor System	0	0	1	0	-	-	0	1	0	0	0	1	0
LH - External Cargo Truss (Mini-Hab & PLM)	1	0	1	0	-	-	0	1	0	0	0	1	0
Lunar Mobility Chassis (MC)													
MC - Structure Frame	0	0	1	0	-	-	0	1	0	0	0	1	0
MC - Structure Suspension	0	0	1	0	-	-	0	1	0	0	0	1	0
MC - Structure Steering Mechanism	0	0	1	0	0	-	0	1	0	0	0	1	0

Figure B.3 (Contd.) Innovative Design Technology Sub-Categories

3. Innovative Design

3.15. Composite overwrap pressure vessels

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
Experience Level (1 low-5 High)													
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin													
Crew Module Aeroshell													
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs													
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank													
EDS Intertank													
EDS LH2 Tank													
LSAM Shroud													
Engine Components													
Lunar Lander	1	1	0	0	-	-	0	1	0	0	0	1	0
Descent Stage LO2 Tank													
Descent Stage Intertank	1	1	0	0	-	-	0	1	0	0	0	1	0
Descent Stage LH2 Tank													
Descent Stage System Supports	1	1	0	0	-	-	0	1	0	0	0	1	0
Ascent Stage LO2 Tank	1	1	0	0	-	-	0	1	0	0	0	1	0
Ascent Stage LH2 Tank (CH4?)													
Ascent Stage Support Platform													
Ascent Stage Crew Cabin													
Lunar Habitat													
LH - Dome													
LH - Barrel													
LH - Internal Frames													
LH - Legs / Ground Support System													
LH - Floor System													
LH - External Cargo Truss (Mini-Hab & PLM)													
Lunar Mobility Chassis (MC)													
MC - Structure Frame													
MC - Structure Suspension													
MC - Structure Steering Mechanism	5	1	1	1	-	-	3	3	1	5	0	0	1

3.16. Crashworthiness incorporated in design

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
Experience Level (1 low-5 High)													
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell	5	5	5	5	-	-	3	3	5	5	1	5	5
Crew Module Crew Cabin	5	3	5	1	-	-	0	3	1	5	0	1	3
Crew Module Aeroshell													
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs													
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank													
EDS Intertank													
EDS LH2 Tank													
LSAM Shroud													
Engine Components													
Lunar Lander	3	1	1	3	-	-	-	3	3	5	0	5	3
Descent Stage LO2 Tank	3	1	1	1	-	-	-	3	1	5	0	5	3
Descent Stage Intertank	3	1	1	3	-	-	-	3	3	5	0	5	3
Descent Stage LH2 Tank	5	3	3	1	-	-	-	3	1	5	0	5	4
Descent Stage System Supports	5	1	1	1	-	-	-	3	1	0	0	5	3
Ascent Stage LO2 Tank	5	1	1	1	-	-	-	3	1	0	0	5	3
Ascent Stage LH2 Tank (CH4?)	5	3	3	1	-	-	-	3	1	5	0	5	4
Ascent Stage Support Platform	5	3	5	5	-	-	3	3	5	5	3	5	5
Ascent Stage Crew Cabin													
Lunar Habitat													
LH - Dome													
LH - Barrel													
LH - Internal Frames													
LH - Legs / Ground Support System													
LH - Floor System													
LH - External Cargo Truss (Mini-Hab & PLM)													
Lunar Mobility Chassis (MC)													
MC - Structure Frame													
MC - Structure Suspension													
MC - Structure Steering Mechanism	0	0	0	0	0	0	0	0	0	0	0	0	1

3.17. Interaction between components (acoustics issues, payload..)

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
Experience Level (1 low-5 High)													
Ares I	3	1	-	1	-	-	3	3	1	3	0	5	3
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell	3	1	-	1	-	-	3	3	1	5	1	5	3
Crew Module Crew Cabin	3	1	-	1	-	-	3	3	1	5	1	1	2
Crew Module Aeroshell													
LAS Shroud													
LAS Tower													
Engine Components													
Ares V	3	1	3	1	-	-	3	3	1	0	0	5	3
Stage 0 SRBs	3	1	1	1	-	-	3	3	1	5	0	5	3
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank													
EDS Intertank													
EDS LH2 Tank													
LSAM Shroud													
Engine Components													
Lunar Lander	3	0	0	1	-	-	-	3	1	3	0	1	1
Descent Stage LO2 Tank	5	1	1	0	-	-	-	3	0	3	0	1	1
Descent Stage Intertank	3	0	0	1	-	-	-	3	1	3	0	1	1
Descent Stage LH2 Tank	3	1	3	1	-	-	-	3	1	3	0	1	1
Descent Stage System Supports	3	0	0	1	-	-	-	3	1	3	0	1	1
Ascent Stage LO2 Tank	3	0	0	1	-	-	-	3	1	3	0	1	1
Ascent Stage LH2 Tank (CH4?)	3	1	3	1	-	-	-	3	1	3	0	1	1
Ascent Stage Support Platform	3	3	3	3	-	-	3	3	3	3	0	1	3
Ascent Stage Crew Cabin													
Lunar Habitat													
LH - Dome													
LH - Barrel													
LH - Internal Frames													
LH - Legs / Ground Support System													
LH - Floor System													
LH - External Cargo Truss (Mini-Hab & PLM)													
Lunar Mobility Chassis (MC)													
MC - Structure Frame													
MC - Structure Suspension													
MC - Structure Steering Mechanism	0	0	0	0	0	0	0	0	0	0	0	0	1

3.18. Integrated TPS, radiation protection

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
Experience Level (1 low-5 High)													
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell	5	3	5	3	-	-	3	3	3	3	5	5	5
Crew Module Crew Cabin	5	3	5	3	-	-	3	3	3	3	5	5	5
Crew Module Aeroshell													
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs													
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank													
EDS Intertank													
EDS LH2 Tank													
LSAM Shroud													
Engine Components													
Lunar Lander													
Descent Stage LO2 Tank													
Descent Stage Intertank													
Descent Stage LH2 Tank													
Descent Stage System Supports													
Ascent Stage LO2 Tank													
Ascent Stage LH2 Tank (CH4?)													
Ascent Stage Support Platform	5	3	5	3	-	-	3	5	3	3	0	5	4
Ascent Stage Crew Cabin													
Lunar Habitat	5	3	5	5	-	-	5	5	5	3	0	5	5
LH - Dome	5	3	5	5	-	-	5	5	5	3	0	5	5
LH - Barrel													
LH - Internal Frames													
LH - Legs / Ground Support System													
LH - Floor System													
LH - External Cargo Truss (Mini-Hab & PLM)													
Lunar Mobility Chassis (MC)	0	0	0	1	-	-	1	3	1	3	0	5	1
MC - Structure Frame													
MC - Structure Suspension													
MC - Structure Steering Mechanism	-	1	1	0	-	-	-	1	0	5	0	5	1

3.19. Lightweight mechanisms for load transfer

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
Experience Level (1 low-5 High)													
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin													
Crew Module Aeroshell													
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs													
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank													
EDS Intertank													
EDS LH2 Tank													
LSAM Shroud													
Engine Components													
Lunar Lander													
Descent Stage LO2 Tank													
Descent Stage Intertank													
Descent Stage LH2 Tank													
Descent Stage System Supports													
Ascent Stage LO2 Tank													
Ascent Stage LH2 Tank (CH4?)													
Ascent Stage Support Platform													
Ascent Stage Crew Cabin													
Lunar Habitat													
LH - Dome													
LH - Barrel													
LH - Internal Frames													
LH - Legs / Ground Support System													
LH - Floor System													
LH - External Cargo Truss (Mini-Hab & PLM)													
Lunar Mobility Chassis (MC)													
MC - Structure Frame													
MC - Structure Suspension	5	3	3	3	-	-	1	5	3	3	3	5	4
MC - Structure Steering Mechanism	0	0	0	0	0	0	0	0	0	0	0	0	1

3.20. Methods of preventing damage growth

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
Experience Level (1 low-5 High)													
Ares I													
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin	0	0	0	0	0	0	0	0	0	0	0	0	3
Crew Module Aeroshell	0	0	0	0	0	0	0	0	0	0	0	0	3
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs													
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank													
EDS Intertank													
EDS LH2 Tank													
LSAM Shroud													
Engine Components													
Lunar Lander													
Descent Stage LO2 Tank													
Descent Stage Intertank													
Descent Stage LH2 Tank													
Descent Stage System Supports													
Ascent Stage LO2 Tank													
Ascent Stage LH2 Tank (CH4?)													
Ascent Stage Support Platform													
Ascent Stage Crew Cabin													
Lunar Habitat													
LH - Dome	0	0	0	0	0	0	0	0	0	0	0	0	3
LH - Barrel	0	0	0	0	0	0	0	0	0	0	0	0	3
LH - Internal Frames	0	0	0	0	0	0	0	0	0	0	0	0	1
LH - Legs / Ground Support System													
LH - Floor System													
LH - External Cargo Truss (Mini-Hab & PLM)													
Lunar Mobility Chassis (MC)													
MC - Structure Frame	0	0	0	0	0	0	0	0	0	0	0	0	1
MC - Structure Suspension	0	0	0	0	0	0	0	0	0	0	0	0	1
MC - Structure Steering Mechanism	0	0	0	0	0	0	0	0	0	0	0	0	1

Figure B.3 (Concl.) Innovative Design Technology Sub-Categories

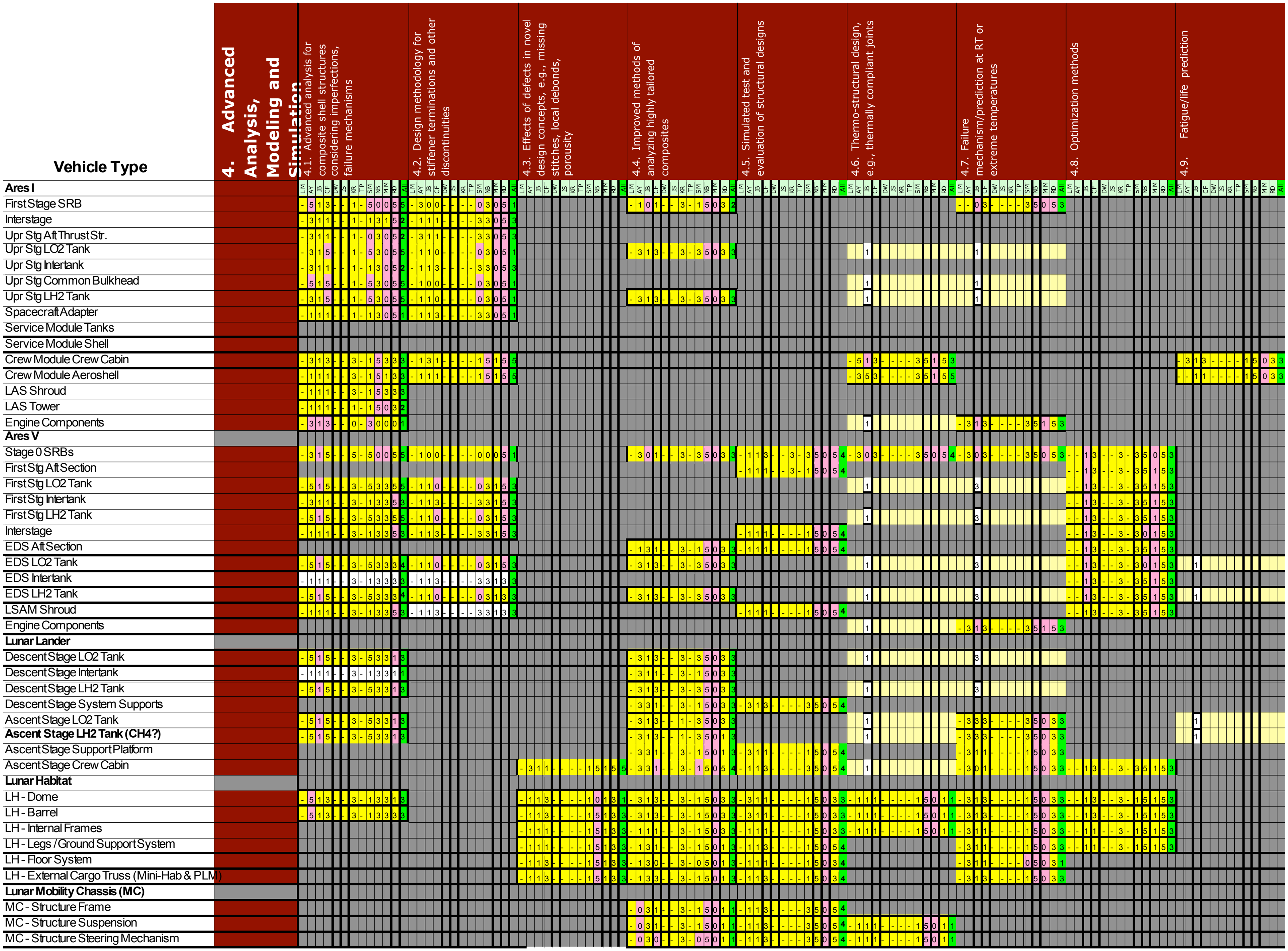


Figure B.4 Advanced Analysis, Modeling and Simulation Technology Sub-Categories

Vehicle Type	4. Advanced Analysis, Modeling and Simulation
Ares I	
First Stage SRB	
Interstage	
Upr Stg Aft Thrust Str.	
Upr Stg LO2 Tank	
Upr Stg Intertank	
Upr Stg Common Bulkhead	
Upr Stg LH2 Tank	
Spacecraft Adapter	
Service Module Tanks	
Service Module Shell	
Crew Module Crew Cabin	
Crew Module Aeroshell	
LAS Shroud	
LAS Tower	
Engine Components	
Ares V	
Stage 0 SRBs	
First Stg Aft Section	
First Stg LO2 Tank	
First Stg Intertank	
First Stg LH2 Tank	
Interstage	
EDS Aft Section	
EDS LO2 Tank	
EDS Intertank	
EDS LH2 Tank	
LSAM Shroud	
Engine Components	
Lunar Lander	
Descent Stage LO2 Tank	
Descent Stage Intertank	
Descent Stage LH2 Tank	
Descent Stage System Supports	
Ascent Stage LO2 Tank	
Ascent Stage LH2 Tank (CH4?)	
Ascent Stage Support Platform	
Ascent Stage Crew Cabin	
Lunar Habitat	
LH - Dome	
LH - Barrel	
LH - Internal Frames	
LH - Legs / Ground Support System	
LH - Floor System	
LH - External Cargo Truss (Mini-Hab & PLM)	
Lunar Mobility Chassis (MC)	
MC - Structure Frame	
MC - Structure Suspension	
MC - Structure Steering Mechanism	

4.10. Probabalistic design

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
Crew Module Crew Cabin	-	-	1	0	-	-	-	-	0	5	0	5	1
Crew Module Aeroshell	-	-	1	0	-	-	-	-	0	5	0	5	1
Ascent Stage Crew Cabin	-	-	1	0	-	-	-	-	0	5	0	5	3

4.11. Progressive failure methods

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
Crew Module Crew Cabin	-	-	1	1	-	-	-	-	1	5	0	5	3
Crew Module Aeroshell	-	-	1	1	-	-	-	-	1	5	0	5	3
Ascent Stage Crew Cabin	-	-	1	1	-	-	-	-	1	5	0	5	3

4.12. Hierarchical analysis

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
Crew Module Crew Cabin	-	-	?	1	-	-	-	-	?	5	0	3	3
Crew Module Aeroshell	-	-	?	1	-	-	-	-	?	5	0	3	3
Ascent Stage Crew Cabin	-	-	?	1	-	-	-	-	?	5	0	3	3

4.13. Prediction of internal and residual stresses and design to minimize or take advantage of such stresses

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
First Stage SRB	-	-	1	0	-	-	-	-	1	-	0	5	3
Upr Stg Aft Thrust Str.	-	-	1	0	-	-	-	-	0	-	0	1	1
Upr Stg LO2 Tank	-	-	1	3	-	-	-	-	3	-	0	1	1
Upr Stg Common Bulkhead	-	-	1	3	-	-	-	-	3	-	0	1	1
Upr Stg LH2 Tank	-	-	1	3	-	-	-	-	3	-	0	1	1
Stage 0 SRBs	-	-	1	0	-	-	-	-	1	3	0	3	3
First Stg Aft Section	-	-	1	0	-	-	-	-	1	3	0	3	3
First Stg LO2 Tank	-	-	1	3	-	-	-	-	3	3	0	3	3
First Stg Intertank	-	-	1	1	-	-	-	-	1	3	0	3	1
First Stg LH2 Tank	-	-	1	3	-	-	-	-	3	3	0	3	3
Interstage (Ares V)	-	-	1	1	-	-	-	-	1	3	0	3	1
EDS Aft Section	-	-	1	1	-	-	-	-	1	3	0	3	3
EDS LO2 Tank	-	-	1	3	-	-	-	-	3	3	0	3	3

4.14. Scaling and validation

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
Stage 0 SRBs	-	-	0	0	-	-	-	-	0	5	0	5	1
First Stg Aft Section	-	-	3	0	-	-	-	-	0	5	0	5	2
First Stg LO2 Tank	-	-	3	1	-	-	-	-	1	5	0	5	3
First Stg Intertank	-	-	3	0	-	-	-	-	0	5	0	5	2
First Stg LH2 Tank	-	-	3	1	-	-	-	-	1	5	0	5	3
Interstage (Ares V)	-	-	3	0	-	-	-	-	0	5	0	5	2
EDS Aft Section	-	-	3	0	-	-	-	-	0	5	0	5	2
EDS LO2 Tank	-	-	3	1	-	-	-	-	1	5	0	5	3
EDS Intertank	-	-	3	0	-	-	-	-	0	5	0	5	1
EDS LH2 Tank	-	-	3	1	-	-	-	-	1	5	0	5	3
LSAM Shroud	-	-	3	0	-	-	-	-	0	5	0	5	2
Engine Components (Ares V)	-	-	0	0	-	-	-	-	0	5	0	5	1
Ascent Stage Crew Cabin	-	-	0	1	-	-	-	-	1	3	0	5	3
LH - Dome	-	-	0	1	-	-	-	-	1	3	0	5	3
LH - Barrel	-	-	0	1	-	-	-	-	1	3	0	5	3
LH - Internal Frames	-	-	0	0	-	-	-	-	0	3	0	5	1
MC - Structure Frame	-	-	0	0	-	-	-	-	0	3	0	5	1

4.15. Coupled Loads analysis

Vehicle Type	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
First Stage SRB	-	-	1	1	-	-	-	-	3	5	0	5	3
Interstage (Ares I)	-	-	1	3	-	-	-	-	3	5	0	1	3
LAS Shroud	-	-	1	1	-	-	3	-	1	5	0	5	3
LAS Tower	-	-	1	3	-	-	3	-	1	5	0	5	3
Stage 0 SRBs	-	-	1	1	-	-	3	-	3	5	0	5	3
First Stg Aft Section	-	0	1	1	-	-	3	-	1	5	0	3	2
First Stg Intertank			1										
EDS Aft Section			1										
LSAM Shroud	-	-	1	1	-	-	3	-	1	5	0	5	2
Ascent Stage Support Platform	-	-	1	3	-	-	3	-	3	5	0	1	1
Ascent Stage Crew Cabin	-	-	1	3	-	-	3	-	3	5	0	5	3
LH - Dome	-	-	1	3	-	-	3	-	3	5	0	1	3
LH - Barrel	-	-	1	3	-	-	3	-	3	5	0	1	3
LH - Internal Frames	-	-	1	1	-	-	3	-	1	5	0	1	1
MC - Structure Frame	-	-	1	1	-	-	3	-	1	5	0	1	

Figure B.4 (Concl.) Advanced Analysis, Modeling and Simulation Technology Sub-Categories

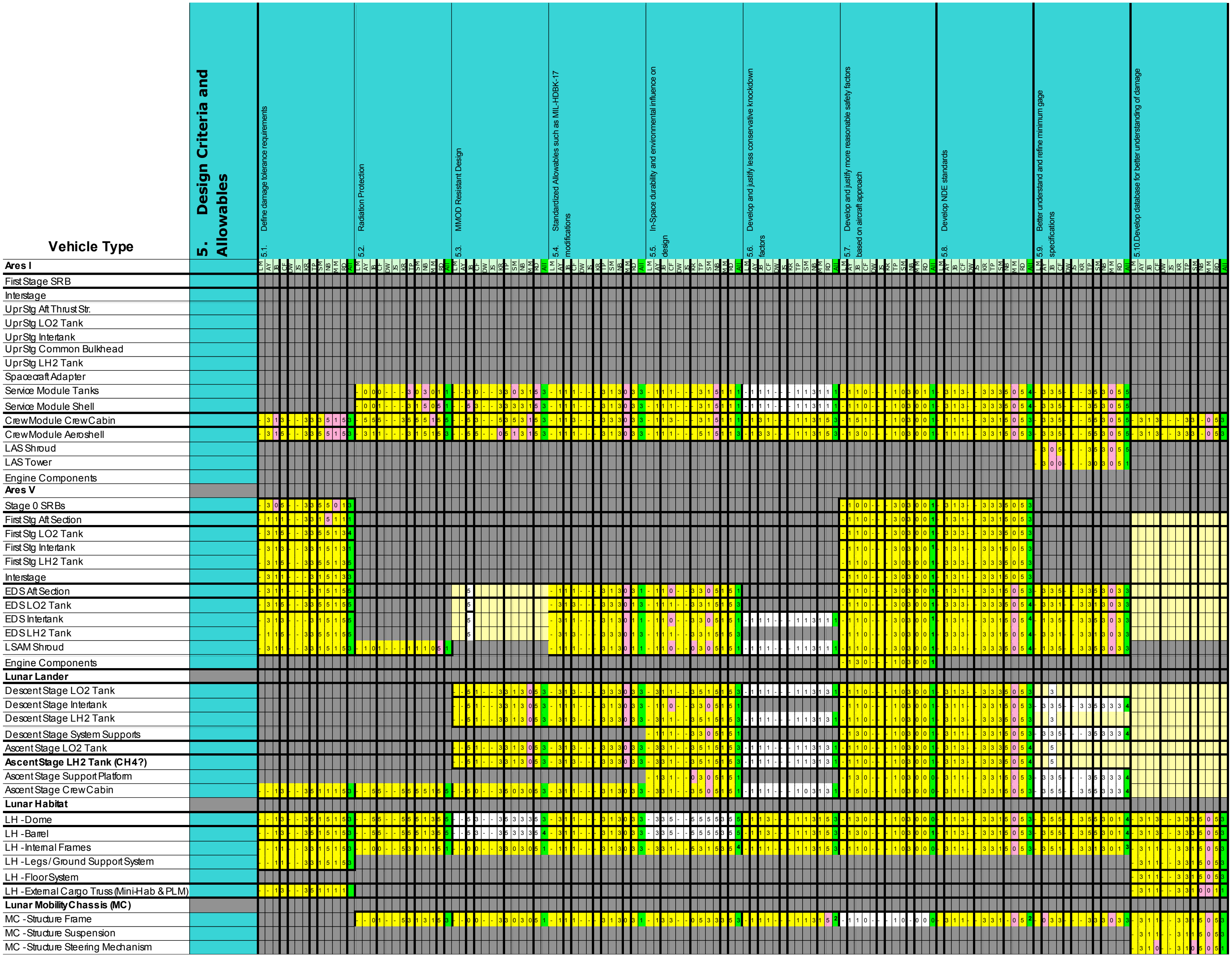


Figure B.5 Design Criteria and Allowables Technology Sub-Categories

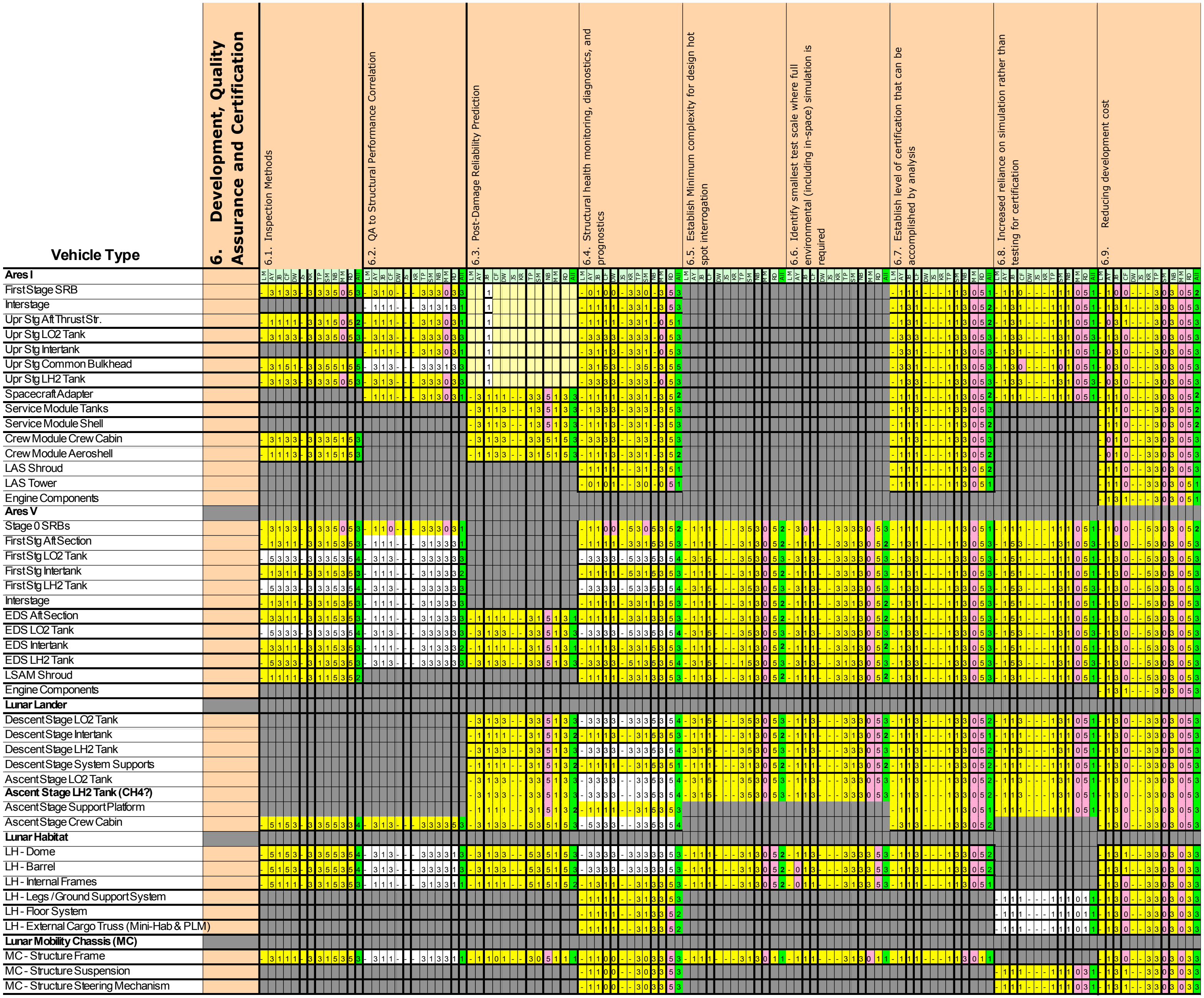


Figure B.6 Development, Quality Assurance and Certification Technology Sub-Categories

Vehicle Type	6. Development, Quality Assurance and Certification	6.10. Improved test methods												
Ares I		LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
First Stage SRB														
Interstage														
Upr Stg Aft Thrust Str.														
Upr Stg LO2 Tank														
Upr Stg Intertank														
Upr Stg Common Bulkhead														
Upr Stg LH2 Tank														
Spacecraft Adapter														
Service Module Tanks		-	1	1	1	-	-	-	1	1	3	0	5	1
Service Module Shell		-	1	1	1	-	-	-	1	1	3	0	5	1
Crew Module Crew Cabin		-	1	1	1	-	-	-	3	1	3	0	5	2
Crew Module Aeroshell		-	1	1	1	-	-	-	3	1	3	0	5	2
LAS Shroud														
LAS Tower														
Engine Components														
Ares V														
Stage 0 SRBs		-	1	1	1	-	-	-	3	1	3	0	5	3
First Stg Aft Section		-	1	1	1	-	-	-	3	1	3	0	5	3
First Stg LO2 Tank		-	3	1	1	-	-	-	3	1	3	0	5	3
First Stg Intertank		-	1	1	1	-	-	-	3	1	3	0	5	3
First Stg LH2 Tank		-	3	1	1	-	-	-	3	1	3	0	5	3
Interstage		-	1	1	1	-	-	-	3	1	3	0	5	1
EDS Aft Section		-	1	1	1	-	-	-	3	1	3	0	5	1
EDS LO2 Tank		-	3	1	1	-	-	-	3	1	3	0	5	3
EDS Intertank		-	1	1	1	-	-	-	3	1	3	0	5	2
EDS LH2 Tank		-	3	1	1	-	-	-	3	1	3	0	5	3
LSAM Shroud		-	1	1	1	-	-	-	3	1	3	0	5	2
Engine Components														
Lunar Lander														
Descent Stage LO2 Tank														
Descent Stage Intertank														
Descent Stage LH2 Tank														
Descent Stage System Supports														
Ascent Stage LO2 Tank														
Ascent Stage LH2 Tank (CH4?)														
Ascent Stage Support Platform														
Ascent Stage Crew Cabin		-	1	1	1	-	-	-	3	1	3	0	5	2
Lunar Habitat														
LH - Dome		-	1	1	1	-	-	-	3	1	3	0	5	2
LH - Barrel		-	1	1	1	-	-	-	3	1	3	0	5	2
LH - Internal Frames		-	1	1	1	-	-	-	3	1	3	0	3	2
LH - Legs / Ground Support System														
LH - Floor System														
LH - External Cargo Truss (Mini-Hab & PLM)														
Lunar Mobility Chassis (MC)														
MC - Structure Frame		-	1	1	1	-	-	-	3	1	3	0	3	1
MC - Structure Suspension														
MC - Structure Steering Mechanism														

Vehicle Type	6.11. Database development												
Ares I	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin													
Crew Module Aeroshell													
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs	-	1	0	1	-	-	-	1	5	5	0	5	3
First Stg Aft Section	-	1	1	1	-	-	-	1	1	5	0	5	3
First Stg LO2 Tank	-	1	1	5	-	-	-	1	5	5	0	5	5
First Stg Intertank	-	1	1	1	-	-	-	1	1	5	0	5	3
First Stg LH2 Tank	-	1	1	5	-	-	-	1	5	5	0	5	5
Interstage	-	1	1	1	-	-	-	1	1	5	0	5	1
EDS Aft Section	-	1	1	1	-	-	-	1	1	5	0	5	1
EDS LO2 Tank	-	1	1	5	-	-	-	1	5	5	0	5	5
EDS Intertank	-	1	1	1	-	-	-	1	1	5	0	5	3
EDS LH2 Tank	-	1	1	5	-	-	-	1	5	5	0	5	5
LSAM Shroud	-	1	1	1	-	-	-	1	1	5	0	5	1
Engine Components													
Lunar Lander													
Descent Stage LO2 Tank													
Descent Stage Intertank													
Descent Stage LH2 Tank													
Descent Stage System Supports													
Ascent Stage LO2 Tank	-	1	1	5	-	-	-	1	5	5	0	5	3
Ascent Stage LH2 Tank (CH4?)	-	1	1	5	-	-	-	1	5	5	0	5	3
Ascent Stage Support Platform	-	1	1	1	-	-	-	1	1	5	0	5	1
Ascent Stage Crew Cabin	-	1	1	1	-	-	-	1	1	5	0	5	1
Lunar Habitat													
LH - Dome	-	3	1	3	-	-	-	1	1	5	0	5	3
LH - Barrel	-	3	1	3	-	-	-	1	1	5	0	5	3
LH - Internal Frames	-	1	1	1	-	-	-	1	1	5	0	5	1
LH - Legs / Ground Support System	-	1	1	1	-	-	-	1	1	5	0	5	1
LH - Floor System	-	1	1	1	-	-	-	1	1	5	0	5	1
LH - External Cargo Truss (Mini-Hab & PLM)	-	1	1	1	-	-	-	1	1	5	0	5	1
Lunar Mobility Chassis (MC)													
MC - Structure Frame	-	1	1	0	-	-	-	1	0	5	0	5	2
MC - Structure Suspension	-	1	1	0	-	-	-	1	0	5	0	5	2
MC - Structure Steering Mechanism	-	1	1	0	-	-	-	1	0	5	0	5	2

Vehicle Type	6.12. Accelerated Aging and accelerated test methods												
Ares I	LM	AY	JB	CF	DW	JS	KR	TP	SM	NB	MM	RD	All
First Stage SRB													
Interstage													
Upr Stg Aft Thrust Str.													
Upr Stg LO2 Tank													
Upr Stg Intertank													
Upr Stg Common Bulkhead													
Upr Stg LH2 Tank													
Spacecraft Adapter													
Service Module Tanks													
Service Module Shell													
Crew Module Crew Cabin													
Crew Module Aeroshell													
LAS Shroud													
LAS Tower													
Engine Components													
Ares V													
Stage 0 SRBs													
First Stg Aft Section													
First Stg LO2 Tank													
First Stg Intertank													
First Stg LH2 Tank													
Interstage													
EDS Aft Section													
EDS LO2 Tank			3										
EDS Intertank													
EDS LH2 Tank			3										
LSAM Shroud													
Engine Components													
Lunar Lander													
Descent Stage LO2 Tank			3										
Descent Stage Intertank													
Descent Stage LH2 Tank			3										
Descent Stage System Supports													
Ascent Stage LO2 Tank			5										
Ascent Stage LH2 Tank (CH4?)			5										
Ascent Stage Support Platform													
Ascent Stage Crew Cabin													
Lunar Habitat													
LH - Dome	-	1	3	3	-	-	-	3	3	3	3	5	3
LH - Barrel	-	1	3	3	-	-	-	3	3	3	3	5	3
LH - Internal Frames	-	1	1	1	-	-	-	3	0	3	3	5	2
LH - Legs / Ground Support System	-	1	1	1	-	-	-	3	1	3	3	5	3
LH - Floor System	-	1	1	1	-	-	-	3	1	3	3	5	2
LH - External Cargo Truss (Mini-Hab & PLM)	-	1	1	1	-	-	-	3	1	3	3	5	2
Lunar Mobility Chassis (MC)													
MC - Structure Frame	-	1	1	3	-	-	-	3	1	3	3	5	2
MC - Structure Suspension	-	1	1	3	-	-	-	3	1	3	3	5	2
MC - Structure Steering Mechanism	-	1	1	3	-	-	-	3	1	3	3	5	2

Figure B.6 (Concl.) Development, Quality Assurance and Certification Technology Sub-Categories

Vehicle Type	7. Threat and Environment	7.1. MMOD protection (lunar/IEO)	7.2. Lunar dust impacts	7.3. Improved leak detection	7.4. Aging in lunar environment	7.5. Static charge issues (on Earth or Moon)	7.6. Lunar polar extreme temperature fluctuations	7.7. Radiation hardened structures	7.8. Noise, insulation	7.9. Coatings and sealants	7.10. Toxicity including outgassing
		LM AY JB CF DW JS KR TP SM NB MM RD All	LM AY JB CF DW JS KR TP SM NB MM RD All	LM AY JB CF DW JS KR TP SM NB MM RD All	LM AY JB CF DW JS KR TP SM NB MM RD All	LM AY JB CF DW JS KR TP SM NB MM RD All	LM AY JB CF DW JS KR TP SM NB MM RD All	LM AY JB CF DW JS KR TP SM NB MM RD All	LM AY JB CF DW JS KR TP SM NB MM RD All	LM AY JB CF DW JS KR TP SM NB MM RD All	LM AY JB CF DW JS KR TP SM NB MM RD All
Ares I											
First Stage SRB									- 1 1 3 - - 3 1 3 - 0 1 1	- 1 1 1 - - - 3 1 5 0 1 1	
Interstage									1		
UprStg Aft Thrust Str.									1		
UprStg LO2 Tank				- 5 3 5 5 - 1 1 5 0 1 5 3		1				- 5 3 1 - - - 3 1 5 0 1 2	
UprStg Intertank											
UprStg Common Bulkhead											
UprStg LH2 Tank				- 5 3 5 5 - 1 3 5 5 1 5 4		- 3 1 3 - - - 3 3 5 0 3 3				- 5 3 1 - - - 3 1 5 0 1 2	
Spacecraft Adapter											
Service Module Tanks		- 3 1 5 3 - 3 3 5 3 3 5 3		- 5 3 5 3 - 1 3 5 5 1 5 4		- 3 1 3 - - - 3 3 5 0 3 3		- 0 0 1 - - - 3 1 5 1 5 2		- 3 1 1 - - - 3 1 5 0 1 2	
Service Module Shell		- 3 3 5 3 - 3 3 5 3 3 5 3				- 3 1 3 - - - 3 3 3 0 3 3		- 1 0 3 - - - 3 3 5 1 5 3			- 3 0 1 - - - 1 3 5 0 1 2
Crew Module Crew Cabin		- 5 3 5 3 - 3 3 5 3 3 5 4		- 5 3 5 3 - 3 5 5 5 1 5 5		- 3 1 3 - - - 3 3 3 0 3 3		- 5 3 5 - - - 3 5 5 1 5 4	- 3 3 3 - - - 3 3 5 1 3 3	- 3 1 3 - - - 3 3 5 1 5 3	- 3 3 5 - - - 5 5 5 3 5 5
Crew Module Aeroshell		- 3 5 5 3 - 3 5 0 3 3 5 4				- 1 1 3 - - - 3 1 3 0 3 3		- 3 3 1 - - - 3 0 5 1 5 3	- 1 3 1 - - 3 3 1 5 1 3 3		- 1 0 1 - - 3 3 3 5 0 1 3
LAS Shroud											
LAS Tower											
Engine Components											
Ares V											
Stage 0 SRBs									- 3 0 3 - - 3 3 3 3 0 3 3		
First Stg Aft Section									1		
First Stg LO2 Tank				- 5 3 5 5 - 1 3 5 5 3 5 5		1				- 3 3 1 - - - 3 1 5 1 3 3	
First Stg Intertank											
First Stg LH2 Tank				- 5 3 5 5 - 1 3 5 5 3 5 5		- 3 1 3 - - - 3 3 5 0 3 3				- 3 3 1 - - - 3 1 5 0 3 3	
Interstage											
EDS Aft Section		1							- 1 1 1 - - - 3 1 1 0 3 1		
EDS LO2 Tank		1		- 5 3 5 5 - 3 5 5 5 3 5 5		1				- 3 3 1 - - - 3 1 5 1 3 3	
EDS Intertank		1									
EDS LH2 Tank		1		- 5 3 5 5 - 3 5 5 1 3 5 5		- 3 1 3 - - - 3 3 5 0 3 3				- 3 3 1 - - - 3 1 5 1 3 3	
LSAM Shroud									5		
Engine Components											
Lunar Lander											
Descent Stage LO2 Tank		- - 3 3 3 - 3 3 3 3 1 5 3	- 3 ? 3 - - - 1 3 1 1 5 2	- 5 3 5 5 - 3 3 5 5 3 5 5	- 1 1 3 - - - 1 3 3 1 5 2	1	- 1 1 3 - - - 1 3 5 1 5 3	- 1 0 3 - - - 1 3 3 1 3 2		- 3 3 1 - - - 3 1 5 1 3 3	
Descent Stage Intertank		- - 1 0 3 - - 3 0 3 1 5 2	- 0 ? 0 - - - 1 0 1 1 5 1		- 1 1 1 - - - 1 1 3 1 5 2		- 1 1 1 - - - 1 1 5 1 5 2	- 1 0 1 - - - 1 1 3 1 3 2		- 3 0 0 - - - 1 0 5 0 3 2	
Descent Stage LH2 Tank		- - 3 3 3 - 3 3 3 3 1 5 3	- 3 ? 3 - - - 1 3 1 1 5 3	- 5 3 5 5 - 3 3 5 0 3 5 4	- 1 1 3 - - - 1 3 3 1 5 2	- 3 1 3 - - - 3 3 5 0 3 3	- 1 1 3 - - - 1 3 5 1 5 2	- 1 0 3 - - - 1 3 3 1 3 3		- 3 3 1 - - - 3 1 5 1 3 3	
Descent Stage System Supports			- 3 ? 3 - - - 1 3 1 1 5 3		- 1 1 1 - - - 1 1 3 1 5 2		- 1 1 1 - - - 1 1 5 1 5 2	- 1 0 1 - - - 1 1 3 1 3 2		- 3 0 0 - - - 1 0 5 0 3 2	
Ascent Stage LO2 Tank		- - 3 3 3 - 1 3 3 3 3 5 3	- 3 ? 3 - - - 1 3 1 3 5 3	- 5 5 5 5 - 1 3 5 3 3 5 5	- 1 5 3 - - - 3 3 3 3 5 3	1	- 1 5 3 - - - 3 3 5 3 5 3	- 1 0 3 - - - 3 3 3 1 3 3		- 3 3 1 - - - 3 1 5 1 3 3	
Ascent Stage LH2 Tank (CH4?)		- - 3 3 3 - 1 3 3 3 3 5 3	- 3 ? 3 - - - 1 3 3 3 5 3	- 5 5 5 5 - 1 3 5 3 0 5 5	- 1 5 3 - - - 3 3 3 3 5 3	- 3 1 3 - - - 3 3 1 0 3 3	- 1 5 3 - - - 3 3 5 3 5 4	- 1 0 3 - - - 3 3 3 1 3 3		- 3 3 1 - - - 3 1 5 1 3 3	
Ascent Stage Support Platform			- 3 ? 1 - - - 1 1 3 3 5 3		- 1 5 1 - - - 3 1 3 3 5 4	- 3 1 0 - - - 3 0 5 0 3 3	- 1 5 1 - - - 3 1 5 3 5 3	- 1 0 1 - - - 3 1 3 1 3 2		- 3 0 0 - - - 1 0 0 0 3 1	
Ascent Stage Crew Cabin							- 5 5 1 - - 5 3 1 5 3 5 5	- 5 5 3 - - - 3 3 5 1 3 4		- 3 3 3 - - 3 3 3 5 1 3 3	- 3 3 5 - - 3 5 5 5 3 5 5
Lunar Habitat											
LH - Dome		- - 3 1 3 - 5 3 5 3 3 5 4	- 3 ? 3 - - - 1 3 1 5 5 3	- 3 5 3 3 - 5 3 1 0 3 5 4	- 3 5 5 - - 5 5 3 3 5 5 5		- 1 5 3 - - 5 5 1 3 5 5 5	- 3 5 5 - - 1 5 5 0 3 5 4		- 3 3 3 - - 3 3 3 5 1 5 3	- 3 3 5 - - 3 5 5 1 5 5 4
LH - Barrel		- - 3 1 3 - 5 3 5 3 3 5 4	- 3 ? 3 - - - 1 3 1 5 5 3	- 3 5 3 3 - 5 3 1 0 3 5 4	- 3 5 5 - - 5 5 3 3 5 5 5		- 1 5 3 - - 5 5 1 3 5 5 5	- 3 5 5 - - 1 5 5 0 3 5 4		- 3 3 3 - - 3 3 3 5 1 5 3	- 3 3 5 - - 3 5 5 1 5 5 4
LH - Internal Frames		- - 1 0 1 - 0 1 0 3 3 5 1	- 3 ? 0 - - - 1 0 1 1 5 2		- 3 5 3 - - - 5 0 3 5 5 4		- 1 5 1 - - 3 5 1 3 5 5 5	- 1 0 0 - - 1 3 0 0 3 5 1		- 3 0 1 - - 3 3 1 5 0 5 3	
LH - Legs/Ground Support System			- 3 ? 1 - - 3 3 0 5 1 5 3		- 1 5 3 - - 5 5 1 1 5 5 4		- 1 5 3 - - 5 5 1 3 5 5 5	- 1 0 0 - - - 3 0 3 1 3 2		- 3 0 1 - - 3 1 1 5 0 3 2	
LH - Floor System			- 3 ? 0 - - - 3 0 3 3 5 3		- 1 5 1 - - - 5 1 1 5 5 3		- 1 5 1 - - 3 5 1 3 5 5 4	- 1 0 1 - - - 5 1 3 1 5 2		- 3 3 1 - - 3 1 1 5 0 3 3	
LH - External Cargo Truss (Mini-Hab & PLM)			- 3 ? 1 - - - 5 0 5 3 5 4		- 1 5 1 - - - 5 1 0 5 5 3		- 1 5 1 - - 3 5 1 3 5 5 4	- 1 0 0 - - - 5 0 0 1 3 1		- 3 3 3 - - 3 3 3 5 0 3 3	
Lunar Mobility Chassis (MC)											
MC - Structure Frame		- - 1 0 0 - 0 3 0 3 1 5 1	- 3 ? 3 - - - 3 1 3 3 5 3	- 1 1 0 0 - - 1 0 0 0 1 0	- 1 5 1 - - 5 5 1 3 5 5 4		- 0 5 1 - - 5 5 1 3 5 5 4	- 0 3 0 - - 1 5 0 1 1 5 2		- 3 1 1 - - 3 1 1 5 0 3 2	- 3 1 1 - - 3 3 1 0 1 5 2
MC - Structure Suspension			- 3 ? 3 - - 5 5 1 3 5 5 4		- 1 5 1 - - 5 5 1 3 5 5 4		- 0 5 3 - - 5 5 1 3 5 5 4	- 0 3 0 - - - 3 0 1 1 5 2		- 3 0 1 - - 3 1 1 5 0 3 2	
MC - Structure Steering Mechanism			- 3 ? 3 - - 5 5 1 3 5 5 4		- 1 5 3 - - 5 5 1 3 5 5 4		- 0 5 3 - - 5 5 1 5 5 5 5	- 0 3 3 - - - 3 0 1 1 3 2		- 3 0 3 - - 3 1 1 5 0 3 2	

Figure B.7 Threat and Environment Technology Sub-Categories

APPENDIX C
Technology Development Road Maps

Technology development roadmaps for 8 of the 12 technologies listed in Figure 20 are presented in this APPENDIX.

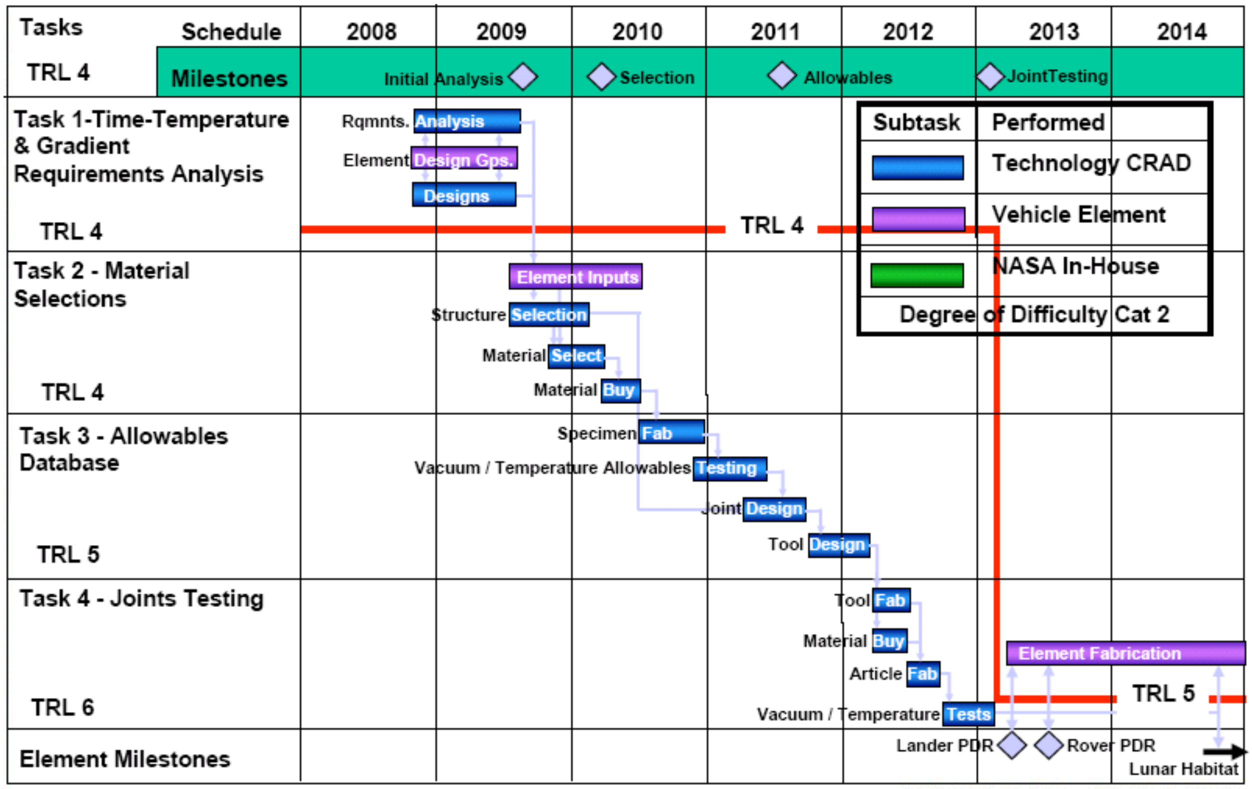


Figure C.1 LUNAR POLAR EXTRME TEMPEATURES

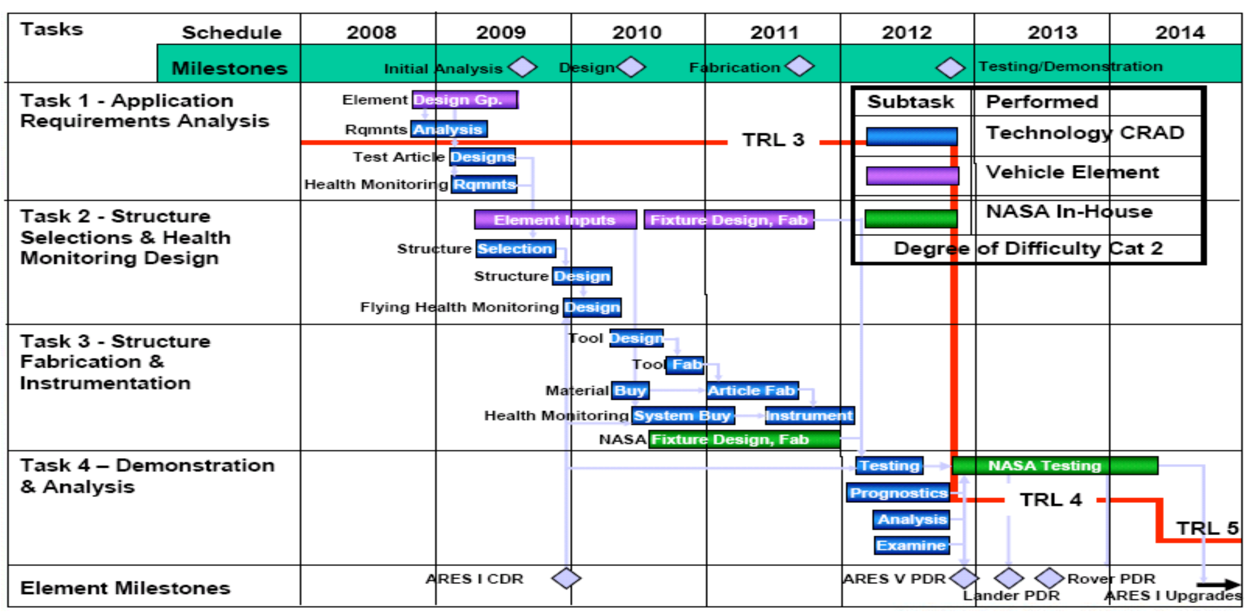
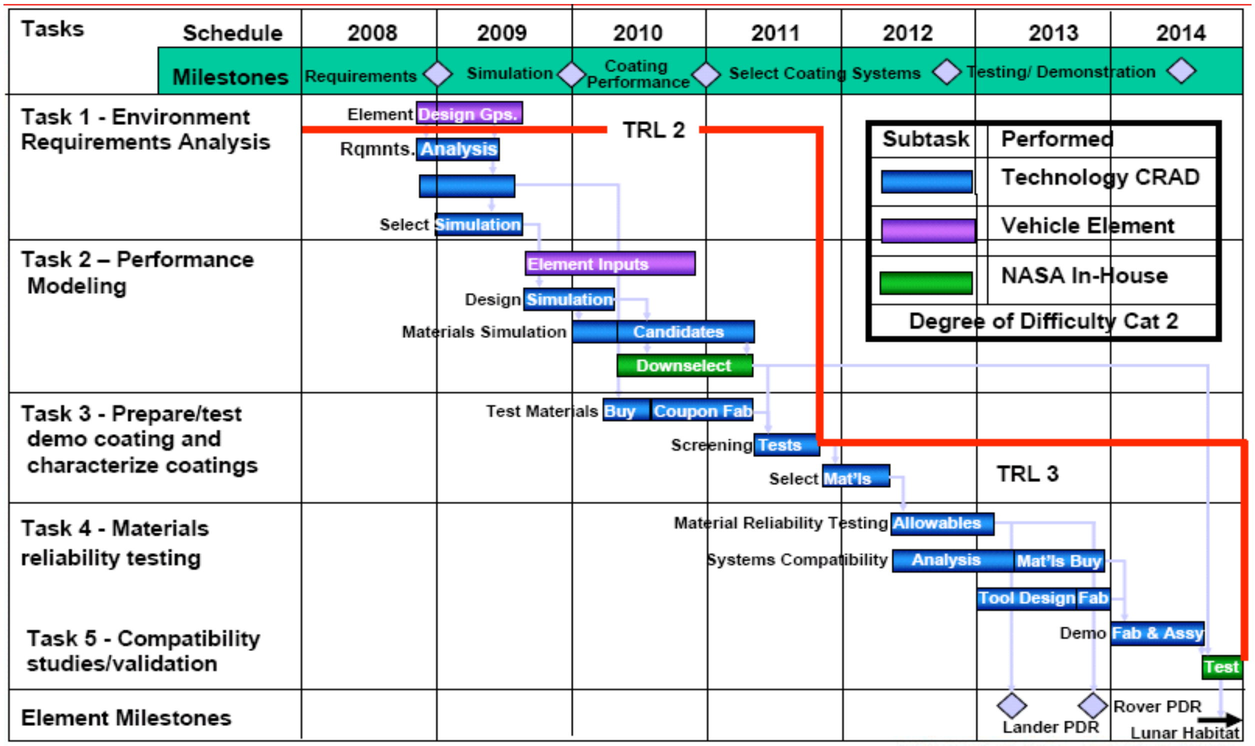


Figure C.2 STRUCTURAL HEALTH MONITORING



C.3 LUNAR DUST IMPACTS

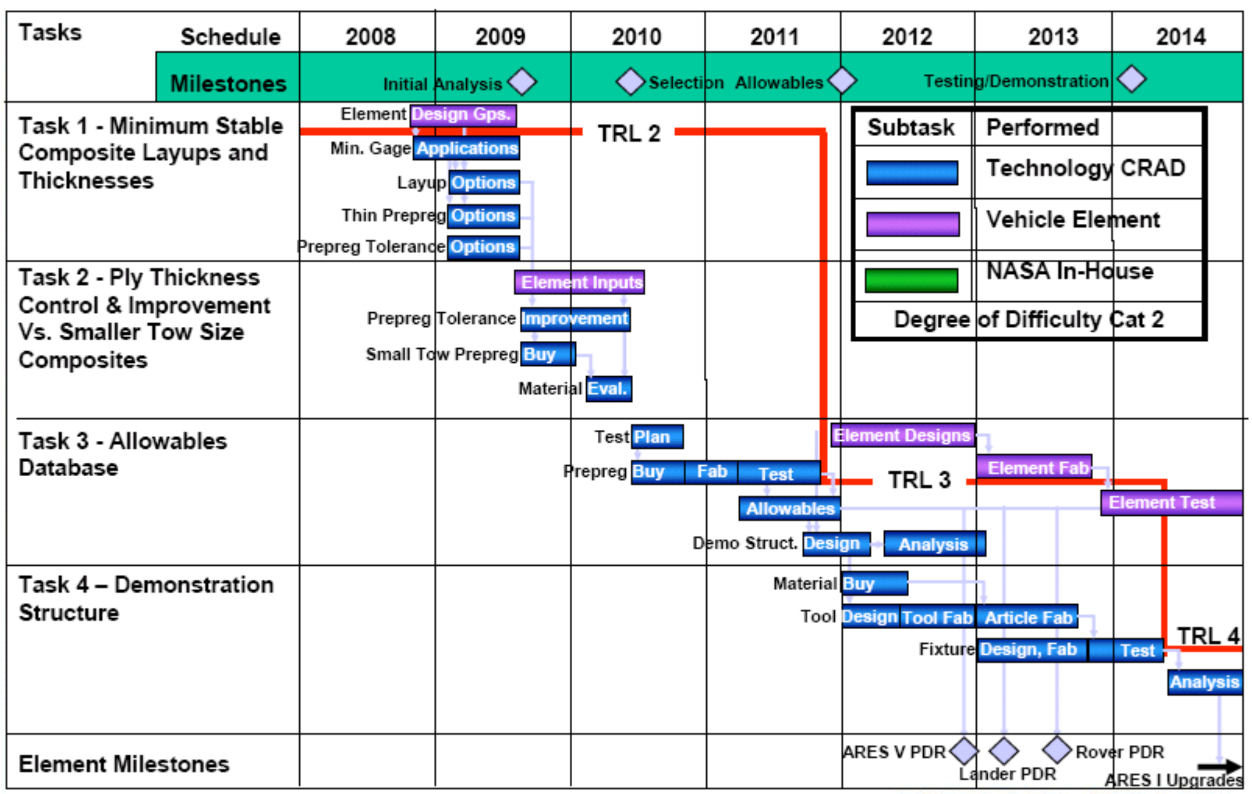


Figure C.4 REFINE MINIMUM GAGE SPECIFICATIONS

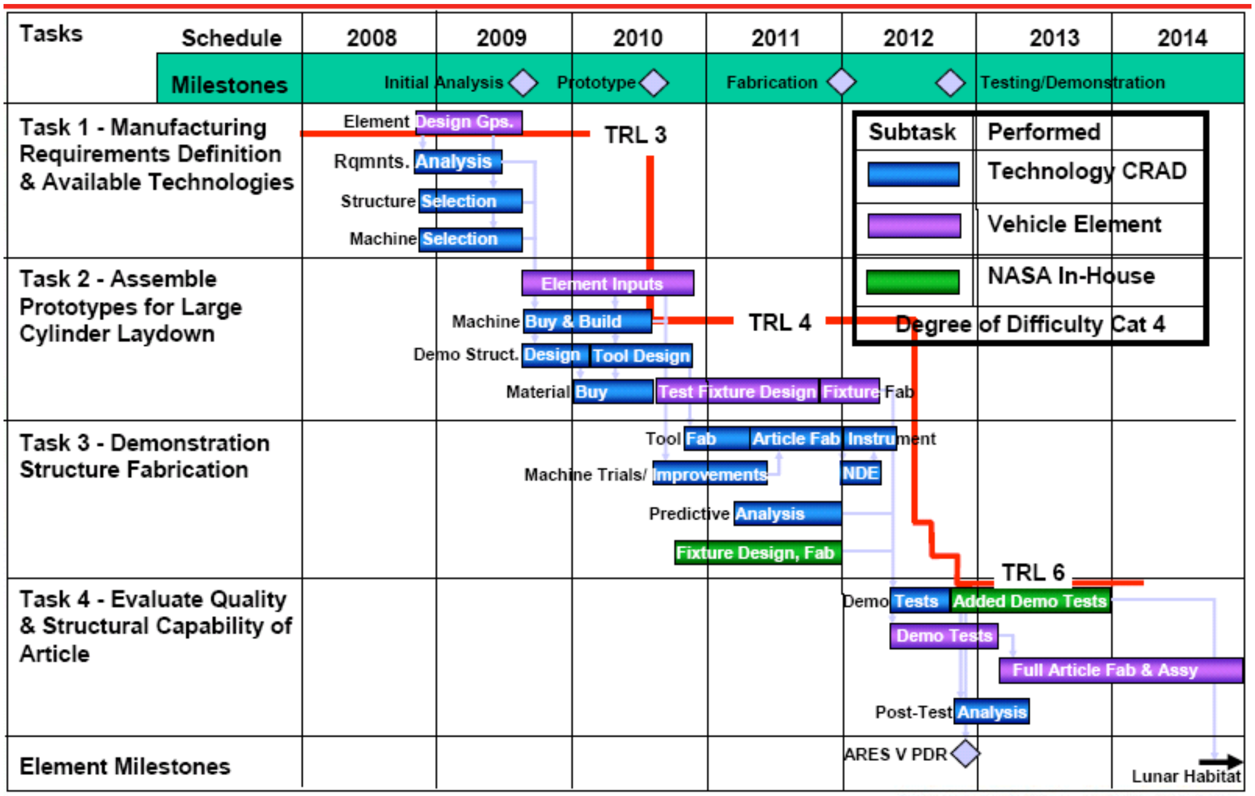


Figure C.5 MANUFACTURING TECHNOLOGIES FOR LARGE SCALE STRUCTURES

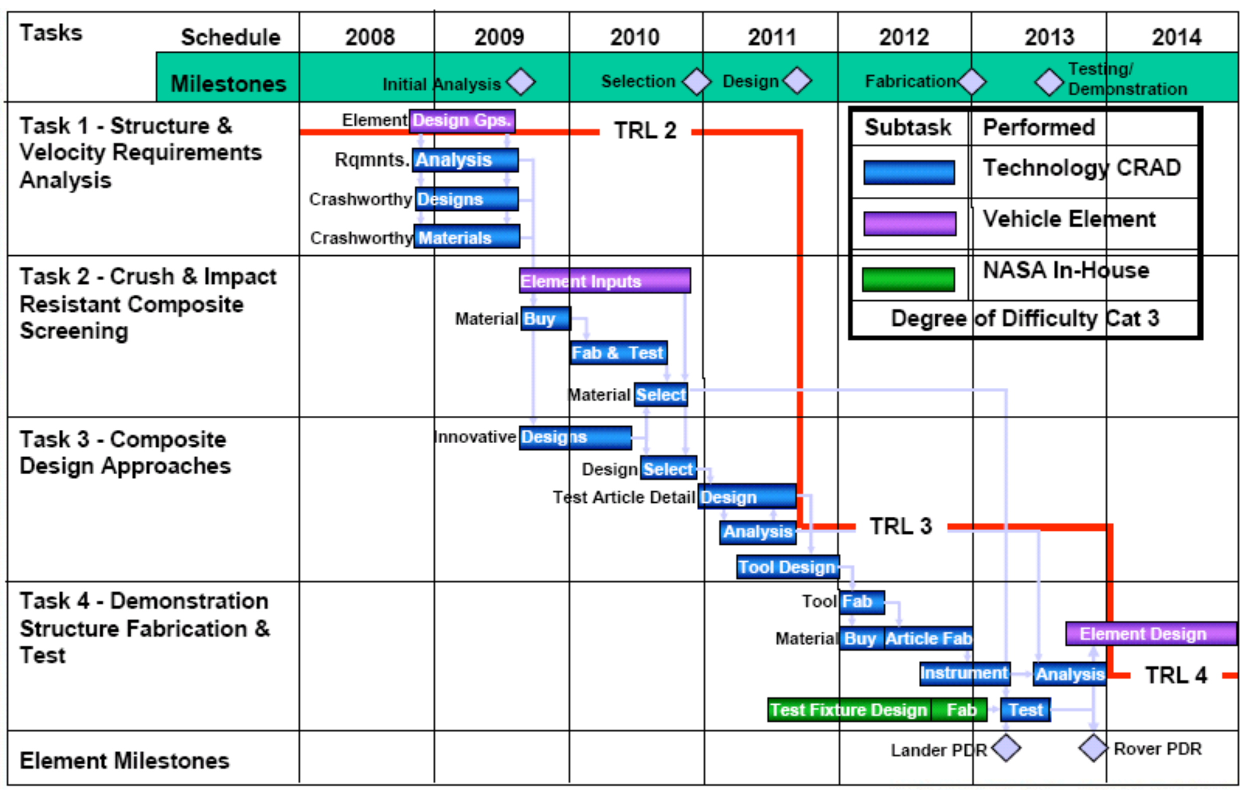


Figure C.6 CRASHWORTHINESS INCORPORATED IN DESIGN

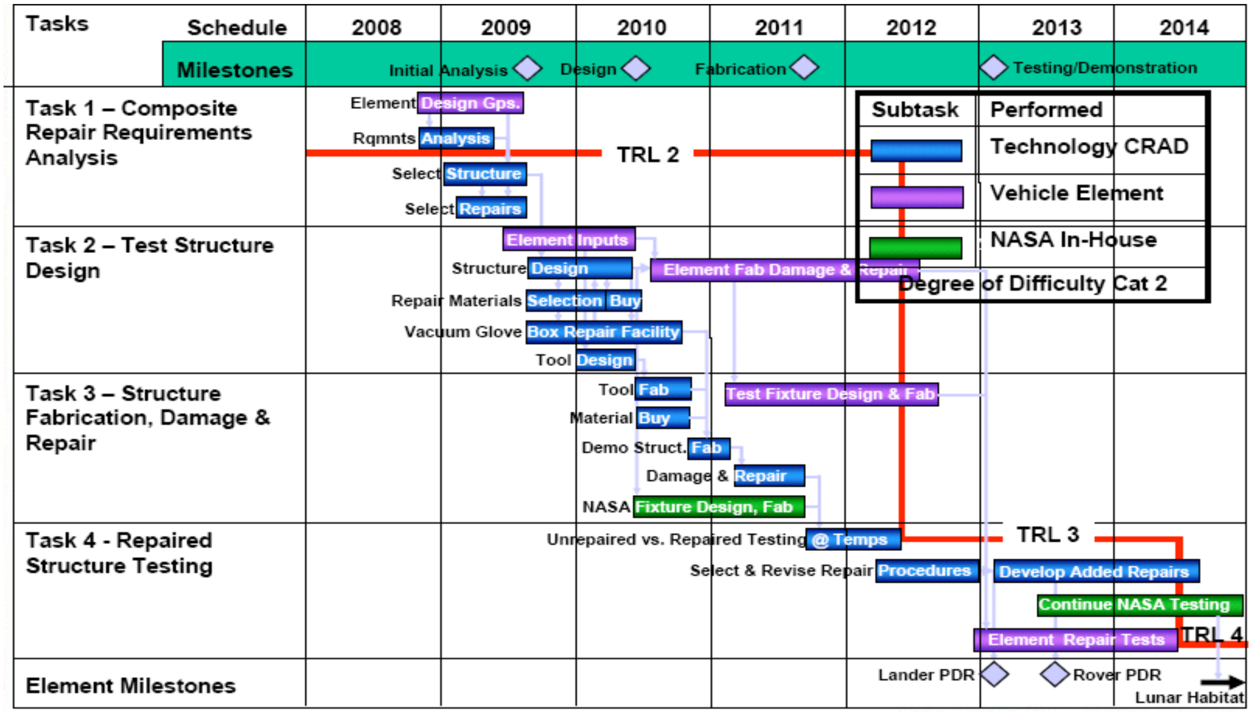


Figure C.7 IN-SPACE/GROUND REPAIR METHODS

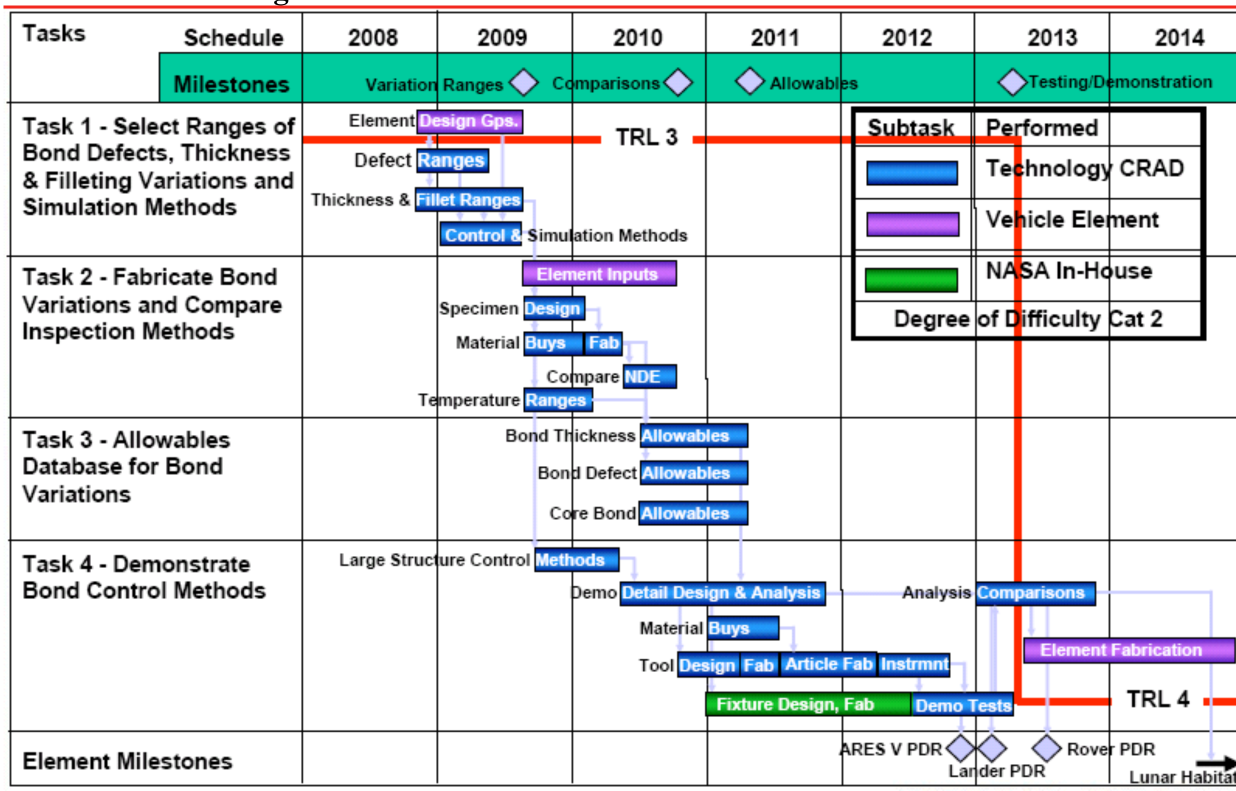


Figure C.8 CO-CURE, CO-BOND AND SECONDARY BOND PROCESSES

APPENDIX D
Northrop Grumman Qualifications

1. Materials and Processes	NGC Qualifications
1.1. Materials for cryo-fuel containment applications (e.g., microcracking, permeability, durability and insulation)	NASA RLV and SLI Programs Technology Area TA-2; White Sands Test Facility Working Group
1.2. Surface preparation and bonding processes for improved adhesive joints	B-2;F/A-18A through G; JSF; F-35; NASA HSR Program; AFRL and NADC CRADs
1.3. Bonded joining concepts, e.g. pi-joints	AFRL Ultralightweight Structures Program; NASA HSR Program
1.4. Co-cure, co-bond, and secondary bond process characterization for repeatable production of bonded	NASA ACT, HSR and ATCAS Programs
1.5. Establish equivalence of out-of-autoclave cure processes by detailed screening, and characterization	NASA RLV and SLI Programs Technology Area TA-2;
1.6. Advanced non-autoclave cure methods	NASA RLV and SLI Programs Technology Area TA-2;
1.7. Long out-time/Long shelf-life materials	Advanced Materials Development Program in Support of YF-23
1.8. Nanocomposite development	Non-Metallic EMI Shielding, AFRL SBIR Phase II; NRO Sponsored Carbon Nanotube Development CRAD

Figure D.1. MATERIALS AND PROCESSES TECHNOLOGIES

2. Manufacturing Methods	NGC Qualifications
2.1. Develop improved non-autoclave processes for traditional carbon/resin systems	NASA RLV and SLI Programs Technology Area TA-2;
2.2. Scale up of manufacturing methods to large (33-ft dia) structures	NASA RLV and SLI Programs Technology Area TA-2 Fabrication of 10-ft Diameter Tank
2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates	F/A-18E/F Duct; F-35 Duct
2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures	Limited
2.5. Vented core and core splicing technology development	NASA RLV and SLI Programs Technology Area TA-2 Fabrication of 10-ft Diameter Tank; Ares I Program (On-going)
2.6. In-process inspection techniques and acceptance methodology	F/A-18E/F
2.7. Nontraditional cure methods such as ultrasonics	NASA RLV and SLI Programs Technology Area TA-2;
2.8. Low-cost tooling	AFRL CRADs
2.9. Improved assembly process such as self-tooling, reducing imperfections and guaranteeing adequate tolerance	Next Generation Strike IRAD

Figure D.2 MANUFACTURING TECHNOLOGIES

3. Innovative Design	NGC Qualifications
3.1. Efficient bolted or bonded joints between large sections	NASA RLV and SLI Programs Technology Area TA-2; ACT and ATCAS Programs, HSR Program
3.2. Multifunctional designs (strength, thermal, radiation, acoustic, …)	B-2;F/A-18A through G; JSF; F-35; AFRL CRADs
3.3. Sandwich Designs	NASA RLV and SLI Programs Technology Area TA-2; ACT and ATCAS Programs, HSR Program
3.4. Iso-, Ortho-Grid Stiffened Designs, selective reinforcement	AFRL Study Contracts
3.5. Hybrid (metal/Composite) stiffened structures	AFRL Durability and Damage Tolerance CRADs
3.6. Tailored (tow steered, variable stiffness) composites	F/A-18E/F Duct; F-35 Duct
3.7. Primarily Bonded structures	F/A-18E/F Duct; F-35 Duct; HSR Program
3.8. Stitched Designs	AFRL Durability and Damage Tolerance CRADs

Figure D.3 INNOVATIVE DESIGN TECHNOLOGIES

3. Innovative Design	NGC Qualifications
3.9. Point load introduction	B-2; F/A-18; F-35; Classified and Unclassified Satellite Programs
3.10. Inflatables	Limited
3.11. In-space/ground repair methods	Apollo Lunar Module; AFRL CRADs; Navy Repair Manuals
3.12. Nanocomposites for load bearing applications and reduce damage growth	AFRL CRADs
3.13. Nanocomposites for non-load bearing applications such as electrical, IVHM, thermal	AFRL SBIR- Nanocomposites for EMI Shielding
3.14. Very high temperature capability as needed for engines and on reentry	NASA Deployable Heat Shield Contract
3.15. Composite overwrap pressure vessels	Satellite Systems Contracts
3.16. Crashworthiness incorporated in design	Apollo Lunar Module Landing Legs with Crushable Aluminum Design

Figure D.3 (Contd.) INNOVATIVE DESIGN TECHNOLOGIES

3. Innovative Design	NGC Qualifications
3.17. Interaction between components (acoustics issues, payload…)	B-2; F/A-18; F-35; Classified and Unclassified Satellite Programs
3.18. Integrated TPS, radiation protection	Limited
3.19. Lightweight mechanisms for load transfer	B-2; F-35; Classified and Unclassified Satellite Programs
3.20. Methods of preventing damage growth	B-2;F/A-18A through G; JSF; F-35; AFRL CRADs; HSR Program

Figure D.3 (Contd.) INNOVATIVE DESIGN TECHNOLOGIES

4. Advanced Analysis, Modeling and Simulation	NGC Qualifications
4.1. Advanced analysis for composite shell structures considering imperfections, failure mechanisms	AFRL Postbuckling CRADs; NASA CRADs; Navy CRADs; Kistler K-1 Launch Vehicle
4.2. Design methodology for stiffener terminations and other discontinuities	B-2;F/A-18A through G; JSF; F-35; AFRL CRADs; HSR Program
4.3. Effects of defects in novel design concepts, e.g., missing stitches, local debonds, porousity	AFRL and Navy Durability and Damage Tolerance CRADs
4.4. Improved methods of analyzing highly tailored composites	Composites Affordability Initiative
4.5. Simulated test and evaluation of structural designs	Composites Affordability Initiative; AFRL Certification by Analysis Task Group
4.6. Thermo-structural design, e.g., thermally compliant joints	B-2; HSR; NASA Deployable Heat Shield Contract
4.7. Failure mechanism/prediction at RT or extreme temperatures	AFRL and NASA Carbon-Carbon Composites Contracts

Figure D.4 ADVANCED ANALYSIS AND SIMULATION

4. Advanced Analysis, Modeling and Simulation	NGC Qualifications
4.8. Optimization methods	B-2; F-35; F/A-18E/F/G; Orion Concept Exploration and Refinement
4.9. Fatigue/life prediction	AFRL Durability and Damage Tolerance Design Guides
4.10. Probabalistic design	NASA GRC CRADs;
4.11. Progressive failure methods	Analytical Studies
4.12. Hierarchical analysis	Limited
4.13. Prediction of internal and residual stresses and design to minimize or take advantage of such stresses	Limited
4.14. Scaling and validation	NASA CRADs
4.15. Coupled Loads analysis	B-2; F-35; Kistler K-1

Figure D.4 (Concl.) ADVANCED ANALYSIS AND SIMULATION

5. Design Criteria and Allowables	NGC Qualifications
5.1. Define damage tolerance requirements	Developed AF Damage Tolerance Design Criteria and Compliance Methodology
5.2. Radiation Protection	Radiation Hardened Avionics and Satellite Systems; Orion CE&R CRAD
5.3. MMOD Resistant Design	Satellite Systems; Orion CE&R CRAD
5.4. Standardized Allowables such as MIL-HDBK-17 modifications	MIL-HDBK-17 Task Group member
5.5. In-Space durability and environmental influence on design	Apollo LM; Chandra

Figure D.5 DESIGN CRITERIA AND ALLOWABLES

5. Design Criteria and Allowables	NGC Qualifications
5.6. Develop and justify less conservative knockdown factors	B-2; F-35; Kistler K-1
5.7. Develop and justify more reasonable safety factors based on aircraft approach	B-2; F-35; Kistler K-1
5.8. Develop NDE standards	B-2; F/A-18; F-35; Kistler K-1
5.9. Better understand and refine minimum gage specifications	Satellite Systems; Orion CE&R CRAD
5.10. Develop database for better understanding of damage	YF-23; B-2; F-35

Figure D.5 (Concl.) DESIGN CRITERIA AND ALLOWABLES

6. Development, Quality Assurance and Certification	NGC Qualifications
6.1. Inspection Methods	B-2; F/A-18; F-35; Kistler K-1
6.2. QA to Structural Performance Correlation	AFRL CRADs
6.3. Post-Damage Reliability Prediction	AFRL, Navy CRADs
6.4. Structural health monitoring, diagnostics, and prognostics	Technology Area 2 and Technology Area 5- IVHM
6.5. Establish Minimum complexity for design hot spot interrogation	AFRL CRADs
6.6. Identify smallest test scale where full environmental (including in-space) simulation is required	AFRL CRADs
6.7. Establish level of certification that can be accomplished by analysis	AFRL, Navy CRADs
6.8. Increased reliance on simulation rather than testing for certification	AFRL CRADs
6.9. Reducing development cost	IRADs
6.10. Improved test methods	NASA, AFRL, Navy CRADs
6.11. Database development	NASA ACT, ATCAS, AFRL and Navy Programs
6.12. Accelerated Aging and accelerated test methods	NASA HSR Program

Figure D.6 DEVELOPMENT, QA AND CERTIFICATION

7. Threat and Environment	NGC Qualifications
7.1. MMOD protection (lunar/IEO)	Orion CE&R Program; NASA RLV TA-2 CRAD
7.2. Lunar dust impacts	Industry Member of NASA Lunar Coatings Working Group (Goddard & Glenn)
7.3. Improved leak detection	NASA SLI TA-2 Program
7.4. Aging in lunar environment	Limited
7.5. Static charge issues (on Earth or Moon)	Limited
7.6. Lunar polar extreme temperature fluctuations	Lunar Lander IRAD Programs
7.7. Radiation hardened structures	AFRL Programs
7.8. Noise, insulation	B-2, Kistler K-1
7.9. Coatings and sealants	DARPA Contract; NASA HR&T Contract; Industry Member of NASA Lunar Coatings Working Group (Goddard &
7.10 Toxicity and outgassing	Satellite Systems

Figure D.7 THREAT AND ENVIRONMENT

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5. Sumrall, Phil “Ares V Overview”, ESMD Technology Exchange Conference, Galveston, Tx, Nov 15, 2007.

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14. ABSTRACT
A trade study was conducted to determine the suitability of composite structures for weight and life cycle cost savings in primary and secondary structural systems for crew exploration vehicles, crew and cargo launch vehicles, landers, rovers, and habitats. The results of the trade study were used to identify and rank order composite material technologies that can have a near-term impact on a broad range of exploration mission applications. This report recommends technologies that should be developed to enable usage of composites on Vision for Space Exploration vehicles towards mass and life-cycle cost savings.

15. SUBJECT TERMS
Ares; Orion; Composites; Structurally efficient; Lightweight; Graphite-epoxy

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